THE APPLICATION OF ARTIFICIAL INTELLIGENCE TO THE DEVELOPMENT OF A DESIGN SUPPORT SYSTEM FOR EXTERNALLY PRESSURISED JOURNAL BEARINGS

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Abstract

This thesis describes an investigation into the development of a design support system for externally pressurised journal bearings. The thesis proposes that expert systems and hypermedia combined with conventional design techniques provide the logical next step for engineering design support systems. This hypothesis is explored through the development and evaluation of these systems. It is possible that this is one of the first attempts to integrate these AI techniques into a mechanical design system. The system mainly consists of six functional modules and two auxiliary modules which include an intelligent selection module, a design module, a hierarchy module, an explanation module, a bearing database module, a report generator module, a help module, and an index module. All modules are hypermedia-based and linked in an associative way which is similar to a designer's thinking style. The selection module is rule-based and each production rule has a refined weighting number. The selection knowledge is acquired and refined from authorative expertise and published sources. The design module successfully incorporates AI techniques with engineering optimisation or other numerical routines to produce an optimal design covering both numerical and qualitative issues. Through all modules working together, the system offers design support covering a full design procedure for an externally pressurised journal bearing from the bearing design specification, through selection of bearing configuration and feeding type to optimisation of bearing parameters and parameter documentation. Human-computer interaction (HCI) and cognitive science issues are explored including the system interface design, system evaluation, design methodology, development and translation, and the relationship between design decision-making and hypermedia semantic structure. The approach to system design is an attempt to bridge the gap between industrial engineers and the available knowledge in externally pressurised bearings design where specialists and experience are needed. The system is implemented on HyperCard on a Macintosh computer.

The extension of the study to consider system development is also described in this thesis. The extension includes developments of a prototype hypermedia-based engineering design environment - HyperCAD and a prototype hypermedia-based

computer assisted learning system HyperCAL for education in mechanical engineering. HyperCAD is a physical implementation of a three dimensional model developed by the author for the engineering design process. HyperCAD is an attempt to develop an engineering design environment which consistently supports all design stages of a design process by integrating the power of different design aids such as expert systems, CAD, FEM, database, spreadsheet, simulation, and other commercial or customised packages. The education system HyperCAL is only a framework with limited subject knowledge so far developed. Both systems demonstrate the potential of using a hypermedia and expert systems approach for general engineering purposes.

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Nomenclature

a	Leakage flow land width
a_s	Width of restrictor slot
A	Total projected bearing area for load or sliding area for friction
A_f	Friction area for journals
A_r	Recess area
b	Inter-recess land width
b_p	Pocket depth
B	Bearing width
B_j	Bearing type or configuration, $j = 1, 2, \ldots\ldots, m$
B_{opt}	Optimum bearing type or configuration, $B_{opt} \in [B_m]$
$\overline{B}$	Flow factor, $\overline{B} = \dfrac{Q\eta}{P_s\beta h_o^3}$
c	Width of axial slot in slotted journal bearing
C_d	Diametral clearance, $C_d = 2h_o$
d	Journal diameter or feed hole diameter
d_c	Diameter of capillary
d_o	Diameter of orifice
d_r	Pocket diameter
D	Journal diameter
e	Journal eccentricity
h	Film thickness
h_o	Film thickness when $P_r = \beta P_s$
H_f	Friction power
H_p	Pumping power
H_t	Total power dissipation
k_i	Rating of operation factor x_i, $i = 1, 2, \ldots\ldots, n$
K	Power ratio, $K = \dfrac{H_f}{H_p}$

$\overline{K}$	MTI design parameter, $\overline{K} = \frac{(1+\delta^2)\lambda_a}{(1+\frac{2}{3}\delta^2)}$
K_c	Capillary constant, $K_c = \frac{128\, l_c}{\pi d_c^4}$
K_g	Gauge pressure ratio for aerostatic journal bearing, $K_g = \frac{P_d - P_a}{P_o - P_a}$
K_{go}	Gauge pressure ratio for concentric aerostatic journal bearing
l_c	Capillary length
L	Bearing length
n	Number of recess or number of slots or orifices per row
N	Rotational speed in r.p.m.
P	Pressure
P_a	Ambient pressure
P_d	Pressure downstream of feed hole or slot in aerostatic bearings
P_r	Recess pressure
P_s	Constant pressure at supply source
q	Flow rate
$\overline{q}$	Dimensionless flow rate, $\overline{q} = \frac{q\eta}{P_s h_o^3}$
R_j	Corresponding score value for bearing type or configuration B_j ($j = 1, 2, \ldots\ldots, m$)
S_h	Hydrostatic Sommerfeld number, for journal bearings $S_h = (\frac{\eta N}{P_s})(\frac{D}{C_d})^2$
T_d	Journal tolerance
T_D	Bearing housing tolerance
ΔT	Maximum temperature rise
U	Bearing journal surface speed
W	Static bearing film force or load
W'	Extreme load
w_{ij}	Weighting number, $i = 1, 2, \ldots\ldots, n$, $j = 1, 2, \ldots\ldots, 7$
x_i	Operation factor, $i = 1, 2, \ldots\ldots, n$
X_i	Question and answer pairs, $i = 1, 2, \ldots\ldots, n$
y	Length of restrictor slot

y_j	Bearing type rating, j = 1, 2, ..., 7
Y_j	Bearing type, j = 1, 2, ..., 7
z	Thickness of restrictor slot
α	Angle of inter-recess land
β	Pressure ratio when $h = h_o$, $\beta = \frac{P_r}{P_s}$
δ	Inherent compensation factor, $\delta = d^2/(4d_r h_o)$ for pocketed orifices; $\delta = d/(4h_o)$ for annular orifices.
γ	Circumferential flow factor for journal bearings
ε	Eccentricity ratio, $\varepsilon = \frac{e}{h_o}$
η	Dynamic viscosity
θ	Angular position around journal bearing
λ	Bearing film stiffness
$\overline{\lambda}$	Dimensionless stiffness, $\overline{\lambda} = \frac{\lambda h_o}{P_s LD}$
$\overline{\lambda_a}$	Dimensionless air bearing stiffness, $\overline{\lambda_a} = \frac{\lambda h_o}{(P_s - P_a)LD}$ $(\varepsilon = 0)$
ρ	Density

Contents

Part II: Development of the system

Part IV: General conclusions

Part I Basis

Chapter 1 Introduction

1.1 History of fluid film bearings

The development and wide acceptance of the steam engine in the early 19th century brought about an industrial need for both journal and thrust bearings. Since then, various types of bearings such as rolling bearings, rubbing bearings, oil impregnated porous metal bearings, and fluid film bearings have been designed and applied in industry. Wherever there is machinery there are bearings, i.e. those elements of machines whereby forces are transmitted between solids which are moving relative to each other.

Fluid film bearings are bearings in which the opposing or mating surfaces are completely separated by a layer of fluid lubricant. In general, it refers to externally pressurised (hydrostatic or aerostatic) bearings and self-acting or hydrodynamic bearings. The hydrostatic principle was introduced by L.D. Girard as early as 1850s[1]. However, the industrial applications of fluid film bearings did not broadly occur until the early 20th century. The principle was first applied in high-pressure water-fed hydrostatic bearings employed for a system of railway propulsion based on a type of linear impulse turbine[1]. The principle was fully demonstrated at the 1878 Paris Industrial Exposition. A heavy block with four feet rested steadily on a steel plate. When oil was pumped down each leg the block floated on films of lubricant and could be moved with astonishing ease. In 1917, Lord Rayleigh provided the first analysis of a simple form of thrust bearing based on the hydrostatic principle[1]. He solved the equations for the bearing load, flow rate and frictional torque. He also made a model in which two flat ground pennies formed the opposing bearing surfaces and the lubricant was water supplied from a tap. Hodgekinson in 1923 patented a hydrostatic bearing with recesses fed through restrictors[2]. The principle can be applied equally to gas- and liquid-fed bearings of various shapes. In October 1947, the great 200 in (5,080 mm) diameter Halle optical telescope was completed on Mount Palomar, California in U.S.A.[3]. It was said to be one of the most spectacular demonstrations of the merits of fluid film bearings.

Fluid film bearings are widely applied in industry in a large variety of applications using liquid and gas lubrication. Inertial gyroscopes, for example, which run at high speeds and low loads, were fitted with self-acting gas bearings in the late 1950s and the reduced friction led to a new generation of precision navigational aids[4]. Through a number of developments, fluid film bearings have established themselves as an extremely important class of machine elements widely used in automotive, aircraft, machine tools and domestic appliances[4]~[7].

1.2 Externally pressurised journal bearings

Externally pressurised journal bearings represent a commonly employed group of fluid film bearing configurations. Within the group there are various sub-groups including combined journal and thrust, conical, and spherical configurations. A family tree of externally pressurised journal bearings is illustrated in Figure 1.1. Hydrostatic and aerostatic journal bearings are used in many engineering applications, especially in the machine tools industry[2][8].

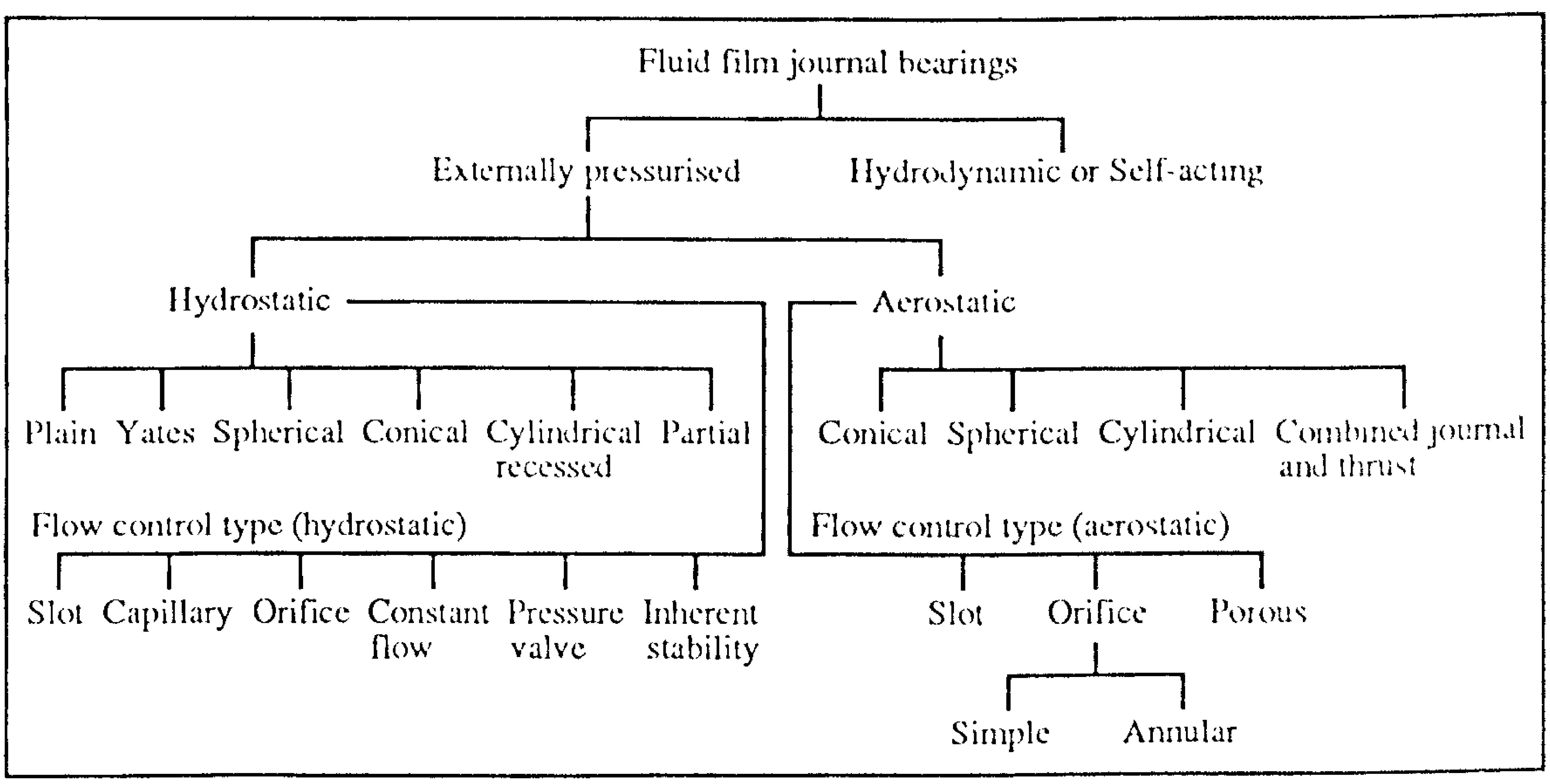


Figure 1.1 A family tree of externally pressurised journal bearings

An externally pressurised fluid film journal bearing is essentially a ring of hydrostatic or aerostatic pads encircling a shaft as shown in Figure 1.2. The bearing pads and the

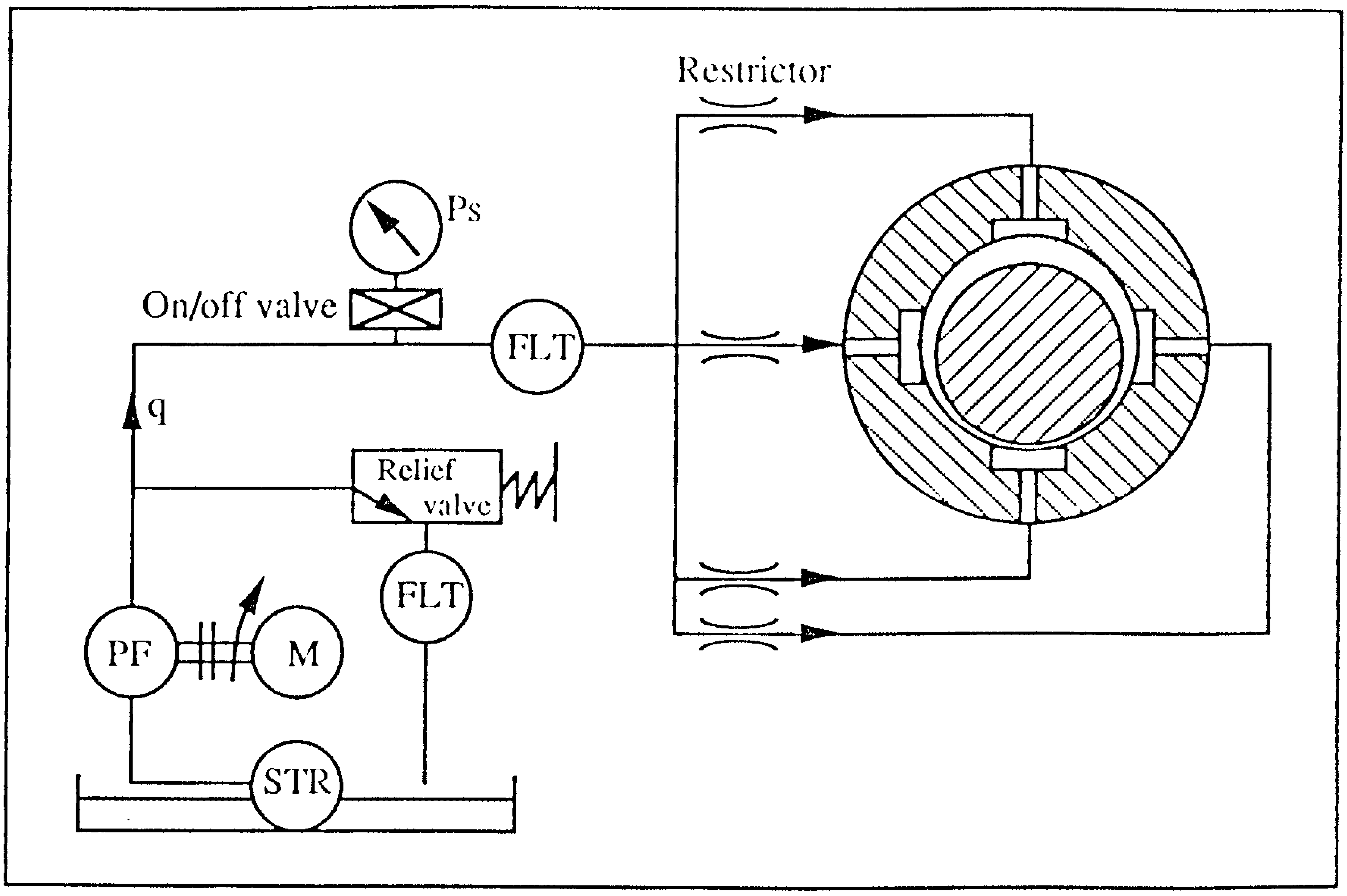


Figure 1.2 A typical externally pressurised fluid film journal bearing

opposing surfaces are separated by a film of fluid lubricant supplied under pressure. The pressure causes fluid to flow axially through the bearing clearance to the ends of the bearing. Under the action of pressure gradients in the circumferential direction, fluid may also flow circumferentially around the shaft. The fluid lubricant is supplied to the bearing via restrictors which may be capillary, orifice, slot, porous surface, et cetera. Because of the usage of restrictors, the effect of changes in load on the film thickness can be made very small, i.e. the bearing can be made stiff to external radial forces. The pressure within the bearing system is maintained by means of an external pump.

With appropriate design, a hydrostatic or aerostatic bearing may have many advantages even though there are also disadvantages associated with the bearing which must be taken into account when evaluating an application. The advantages and disadvantages of externally pressurised journal bearings are summarised in Table 1.1. All these advantages are not necessarily easily obtained in any one particular application.

<table>
<tr><th colspan="2">Advantages</th><th colspan="2">Disadvantages</th></tr>
<tr><th>Hydrostatic</th><th>Aerostatic</th><th>Hydrostatic</th><th>Aerostatic</th></tr>
<tr><td colspan="2">(a) low friction at low speeds,
(b) precise axis definition,
(c) low or zero wear rate giving a long life,
(d) averaging of spindle manufacturing errors,
(e) high stiffness and predictability obtainable by attention to the control device,</td><td colspan="2">(a) auxiliary equipment such as pump, filters, supply lines required,
(b) high initial cost for small bearings,</td></tr>
<tr><td>(f) high damping,
(g) the hydrostatic effect can in some cases be used to offset whirl.</td><td>(f) capability of operating at very high rotational speed,
(g) low noise and vibration levels,
(h) capability of operating at very high or very low temperatures,
(i) cool running due to low friction.</td><td>(c) most supply pumps are noisy, particularly at high supply pressures.</td><td>(c) the bearing size may be large compared to other types of bearings if it is required to operate at high loads,
(d) limited load-carrying capacity,
(e) small clearances and restrictors required,
(f) low damping at resonant frequency,
(g) careful design required to avoid pneumatic hammer.</td></tr>
</table>

Table 1.1 Advantages and disadvantages of externally pressurised journal bearings

The practical application of externally pressurised fluid film journal bearings ranges from the small, precision gas bearings used for the gimbal support of inertial guidance gyroscopes to huge oil lubricated bearings supporting radio telescopes. Figure 1.3 shows typical applications of externally pressurised bearings. For the applications listed, externally pressurised bearings have been considered to be superior to other

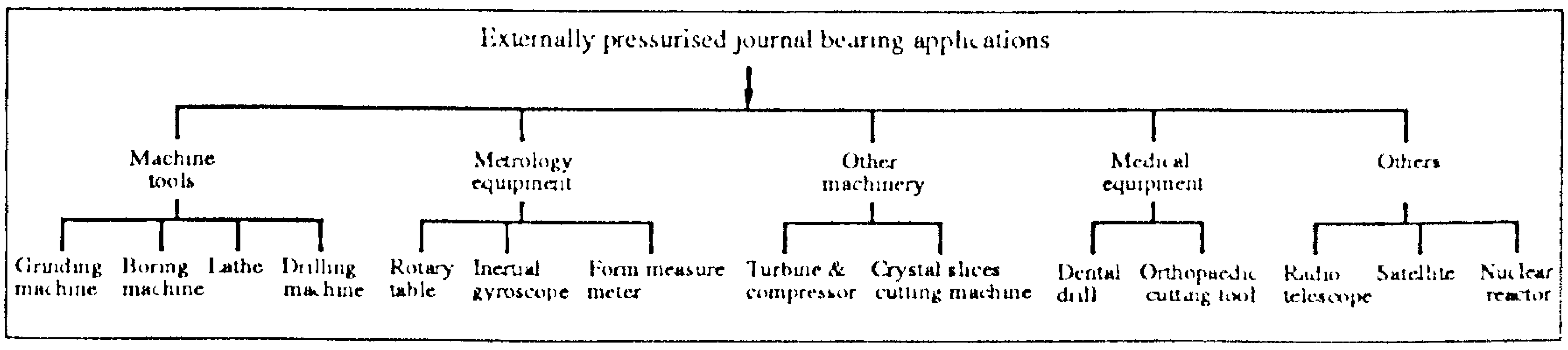


Figure 1.3 Typical applications of externally pressurised journal bearings

bearing types[9].

1.3 Origins and aim of the investigation

Although there are many publications, design manuals and computer programs for bearing design, the design of hydrostatic and aerostatic journal bearings remains a specialist task. Specialist knowledge and experience are required. Computer programs are not generally available for bearing design. The availability of powerful personal computers and artificial intelligence (AI) techniques presents the potential of representing specialist knowledge and complex relationships for the benefit of non-specialist designers. The investigation commenced on the basis of exploring this potential. It was decided to develop an intelligent bearing design support system, with the broad aim of providing effective technical support, flexibility, efficiency and explanation, for non-specialist designers. The system should allow a designer to achieve an optimal design taking into account numerical and qualitative issues. The system was required to be a knowledge-bank containing bearing knowledge using multimedia and knowledge-based representation. The expertise accumulated in Liverpool John Moores University since the early 1970s forms a major part of the system knowledge base. The knowledge also comes from publications from other sources. The system was required to be implemented on a PC platform for portability, ease of access and application.

The investigation was carried out with four main objectives:

(1) To determine strategies for selection of bearing type.

(2) To develop a general design approach for both hydrostatic and aerostatic journal bearings.

(3) To develop an intelligent design support system for externally pressurised fluid film journal bearings.

(4) To explore the potential of extending the system concept to general engineering design and computer assisted learning materials.

1.4 The scope of the investigation

The thesis is presented in four parts. Part I reviews bearing design techniques and includes a preliminary study of various AI approaches such as knowledge-based systems, expert systems, hypermedia and the integration of a range of techniques. In Chapter 4, the development of a general design approach for both hydrostatic and aerostatic journal bearings is presented.

Part II concerns the development of an intelligent design support system for bearings. The system was developed by integrating AI technology with conventional bearing design techniques. The methodology of developing the system is discussed including the processes of knowledge acquisition and representation, system prototyping, system validation, and human-computer interaction (HCI) issues. System functionality is discussed with reference to design examples of system operation.

In Part III applications of system concepts in engineering design and education are presented. The development of two prototype systems is described. One is a hypermedia-based engineering design environment (HyperCAD), the other is a hypermedia-based computer assisted learning system (HyperCAL) for education in mechanical engineering. These developments are presented because the design and education domains demonstrate essential problems of human-computer interaction and cognition in engineering applications.

Part IV presents conclusions on the advantages and difficulties of designing complex software systems for non-specialists using expert systems and hypermedia. Recommendations are made for future work.

Chapter 2 Review of design techniques for externally pressurised bearings

2.1 Introduction

A large number of publications dealing with analysis of external pressurised bearings and the development of design procedures provide a reasonable confidence in the design of bearings for most applications although specialist design and development is still required for heavily loaded bearings[1]. Design procedures are usually based on one of the following three types of approach:

- Procedures based on design data and charts.
- Optimal design rules and computerised solutions.
- Design incorporated with AI.

The development of the subject of bearing design has progressed from optimisation based on a straight forward design rules approach to optimisation based on both quantitative and qualitative issues, even though the last goal is still far from being fully achieved. The rapid development of computing power gives an added stimulus to the development of improved design techniques.

2.2 Design data

2.2.1 Hydrostatic journal bearings

Much of the basic information needed for designing a hydrostatic bearing is available in the form of design data and charts[1].

Raimondi and Boyd[10] first presented a complete theoretical analysis for a four-recess hydrostatic journal bearing subjected to static load. The performance characteristics of the bearing were obtained by considering the continuity of flow into and from each recess. The analysis included the effects of pressure induced (Poiseuille) flow between adjacent recesses (based on a one-dimensional flow model) and a semi-quantitative appraisal of the effects of shaft rotation or velocity induced (Couette) flow was described.

Rippel[11] subsequently presented a detailed analysis, a design procedure and design data for various configurations of hydrostatic journal bearings. The design procedure also included some worked examples which are useful references for designers.

Cowley and Kher[12] presented a design procedure based on thin-land assumptions for a capillary compensated journal bearing subjected to a static load neglecting the effect of rotation induced (Couette) flow. Therefore their procedure can only give valid predictions at low speeds.

Davies[13] outlined a general theoretical analysis for multi-recess hydrostatic journal bearings, which takes into account the effect of shaft rotation. The analysis was applied to a particular orifice compensated bearing. The interaction between the bearing pressure ratio, speed variable, and the direction of the applied load were all investigated.

An investigation into the design of various shapes and types of hydrostatic bearings was carried out by O'Donoghue and Rowe[14]~[15]. The design data obtained from their results were presented in both analytical and graphical forms. Results were presented for thin-land bearings for simplicity and for thick-land bearings based on finite difference techniques.

Until 1970 most of the publications were concerned with the steady state behaviour of hydrostatic bearings and based on assumptions such as an incompressible fluid, constant fluid viscosity, laminar flow, negligible angular shaft misalignment, and negligible elastic deformations of the shaft and housing. Many practical problems range from stability to manufacturing and operating problems. Subsequently, many workers conducted investigations on the analysis and design of bearings in practical conditions taking account of bearing dynamics and other factors such as shaft deflection, fluid viscosity variation, bearing manufacturing errors and bearings with end seals.

Rowe and Stout[16] discussed the problems and effects of the viscosity variations in hydrostatic bearings. Recommendations were made concerning the selection of the control device and the value of design pressure ratio, which should help the designer to cope with varying lubricant temperatures and achieve a satisfactory design.

Rowe and Stout[17] also described the effect of manufacturing errors which may cause serious loss of load capacity and stiffness. A scheme was proposed for suitable selection of clearance limits based on hydrostatic theory and ISO tolerance grades.

Ghosh and Majumdar[18] discussed the design and performance of hydrostatic multi-recess journal bearings under dynamic conditions. Effects of various design parameters on the bearing stiffness and damping were investigated based on first order perturbation theory but without shaft rotation.

By using small displacement analysis, Rowe[19] investigated the dynamic and static properties of recessed hydrostatic journal bearings. Coefficients were presented for hydrostatic stiffness, hydrodynamic stiffness and squeeze damping for capillary, orifice and constant flow control. These coefficients can be used for conservative design and also for predicting the onset of whirl. The results were illustrated by application to rotating and non-rotating load situations.

Andres[20] carried out an experimental analysis of hydrostatic journal bearings with end seals. Results from the analysis show that bearings with end seals have increased damping, better dynamic stability characteristics, as well as low flow rate. End seals are shown to compensate for the effect of liquid compressibility within the recess volume, and produce a net reduction in the whirl frequency ratio for a hydrostatic and hydrodynamic hybrid operation..

General introductions to the subject including detailed design guides for bearings were edited or written by Rohde[21], Barwell[22], and Rowe[23].

2.2.2 Aerostatic journal bearings

In the early 1950s, the development of air-cooled nuclear reactors and high-performance gyroscopes for missiles led to the use of aerostatic bearings which are capable of operating at very high speeds and over a wide range of temperatures even in a radioactive environment.

The principle of operation of the aerostatic journal bearing is essentially similar to that of the hydrostatic journal bearing. However, there are two fundamental differences which must be borne in mind. Firstly air is compressible and secondly its viscosity is between 100 and 1000 times lower than the usual viscosities of oil. The compressibility of air can lead to problems with aerostatic bearings, due to the difficulty of predicting the incidence of pneumatic hammer. Figure 2.1 shows a typical aerostatic journal bearing configuration with orifice feeding holes.

Three major design methods for aerostatic journal bearings have been popularly used since the 1960s[24]. These are the methods of Powell, Mechanical Technology Inc.(MTI) and Constantinescu.

Powell's method[25] starts from a particular value of the gauge pressure ratio K_g. The optimum value is invariably in the region of 0.5 for maximum load capacity for bearings of both simple and annular orifice compensation, although a rather higher K_g value may be chosen in order to minimise gas consumption. First the mean radial clearance of the bearing has to be decided, since this must be made as small as possible to achieve economy of gas consumption and high bearing stiffness but may be determined in the end by the minimum clearance which can be accurately manufactured. Then for one or two rows of feed holes, the size and number of feed holes is calculated. A large number of feed holes was recommended subject to a minimum separating distance. The number of holes is determined by the smallest hole that can be drilled. Powell provided quick and easy to read design charts.

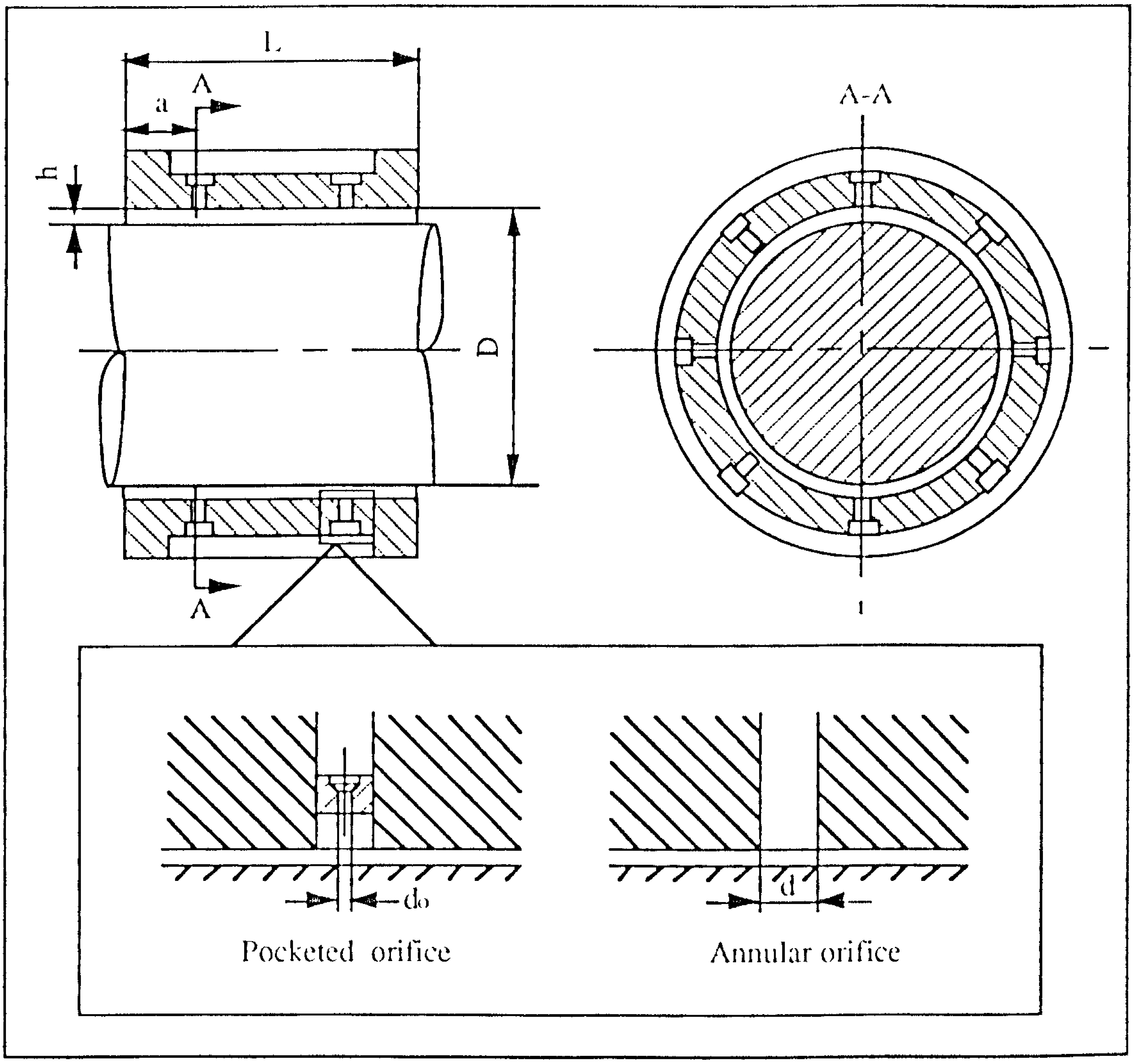


Figure 2.1 A typical aerostatic journal bearing configuration

MTI[26] suggested a minimum number n of orifices dependent on the bearing length-diameter ratio L/D, diameter D, shaft diameter d and whether the bearing has single or double row admission. A refinement was included to account for inherent compensation effects. A major drawback in MTI design charts is that operating lines are given for so many supply pressure ratios that reading values of an essential parameter $\overline{K} = (1+\delta^2)/(1+2\delta^2/3)$. $\overline{\lambda_a}$ in the region of the optimum value of the feeding parameter is very awkward if not impracticable.

Constantinescu[27] assumed for the purposes of analysis, the replacement of the rows of orifices by continuous sources and suggested that this leads to 'surprisingly accurate' results even when the number of orifices is relatively small, e.g. n = 6. Although the bearing condition analysed is specifically at eccentricity ratio $\varepsilon = 0$, the design methods predict operating characteristics with a stated accuracy of 'less than about 10%' when the journal eccentricity ratio $\varepsilon < 0.5$.

Based on any one of above three methods, an aerostatic journal bearing design can be carried out. However, to achieve a successful design, a number of considerations need to be taken into account. These include air-hammer instability, self-excited whirl, very high or very low temperature operations, the selection of the compensation devices e.g. simple orifice, annular orifice, porous matrix, capillary and slot restrictors, manufacturing errors, and material selection to cope with small clearances, dry rubbing and corrosion. There are many published papers[4][28] discussing these problems. In particular, general design data, analysis and experiments are given by Gross[29], Powell[30], Stout and Rowe[31], and Gross[9].

2.2.3 Bearing selection

From a practical viewpoint the selection of the basic attributes of a bearing needs to be carried out at the early stages of a hydrostatic or aerostatic bearing design. The selection of attributes includes the selection of bearing type, bearing configuration, compensation devices, bearing materials and production techniques. The wide range of bearing types and configurations available to the designer increases the difficulty in selecting and optimising the most suitable design for a given application. It is not uncommon in diagnostic studies of tribological failures to find that the problem lies in the use of an inappropriate bearing type or configuration rather than in errors of detailed bearing design[32].

The first logical and reliable bearing selection procedure was provided by Neale[33]. Neale started with a survey of the loads and speeds of operation of bearings in a wide range of machinery and discovered that the range of loads spanned about seven orders of magnitude and the speeds six orders of magnitude. Neale used logarithmic scales to graph the load and speed domains for dry rubbing, rolling, externally pressurised, self-acting, self-contained and porous bearings of various sizes. Superposition of these relationships for bearings of given sizes provided a bearing selection chart of immeasurable value. The approach also contained caveats which took account of special environmental conditions and operating requirements. At a later stage, Neale chaired an I.Mech.E. committee to produce a bearing selection document[34], but the document did not include the selection of externally pressurised bearing types and configurations.

Stout and Rowe[35] provided information relating to the selection of configuration geometry, control devices and materials for both aerostatic and hydrostatic journal bearings. They suggested the following aspects should be considered:

- Selection of the correct tolerance to avoid loss of load capacity and stiffness.
- Initial selection of design parameters for minimum total power dissipation and low temperature rise.
- Selection of a suitable configuration and appropriate manufacturing technique to achieve the required tolerance and economic manufacture.
- Selection of materials.

However, effective strategies need to be investigated and developed for the above selection problems

De Gee[36] investigated the selection of materials for lubricated journal bearings. A number of selection criteria were proposed. The criteria included the material mechanical properties, thermal properties, corrosion rate, behaviour under boundary lubrication conditions, price, behaviour under abrasive conditions, resistance against cavitation erosion, and resistance against electrical discharge pitting.

2.3 Optimal design and computerised solutions

In the early years of development of externally pressurised bearings, bearings were successfully designed for many applications. Though technically successful, the bearings were usually far from optimum and, were often designed by arbitrary methods[4]. Because of a large number of geometrical and functional parameters, it is difficult to achieve an optimum bearing design which reflects the greater or lesser requirements in a particular application for stability, high load capacity, zero friction torque, and low cost.

Optimum design of an externally pressurised bearing should provide both reliability and economic operation. Generally, the following criteria apply to bearing optimal design[37]:

- The load carried should be a maximum for a given fluid flow.
- The stiffness of the bearing (dW/dh) should be maximum.
- The pumping power should be minimum.

Rowe, O'Donoghue and Cameron[38] investigated various criteria that can be applied to the optimal design of hydrostatic bearings. It was suggested that bearing design for low-speed bearings starts from the criterion that maximum load support should be achieved for minimum power expended. The designer can easily vary from this economic condition to achieve other objectives, such as a low temperature rise, a small oil viscosity variation, and small thermal distortions in the machine structure. The optimisation parameter S_h [$S_h = (\eta N/P_s)(D/C_d)^2$] was introduced which has great significance in defining the following characteristics of a hydrostatic bearing:

- The optimum design values for minimum power dissipation.
- Temperature rise proportional to supply pressure.
- The proportions of hydrodynamic and hydrostatic lift in hydrostatic journal bearings.
- The attitude angle between applied load and journal displacement.

For minimum power, high stiffness, and low temperature rise, it was concluded that the bearing design parameters should be selected so that:

- Clearance C_d is an economic minimum.
- Land-width ratio a/L is 0.25 when expressed in an appropriate form.
- High supply pressures are avoided.
- Viscosity is selected to make power ratio $K = H_f/H_p = 1$.

Cusano and Conry[39] used an optimisation method based on mathematical programming for the design of four-recess hydrostatic journal bearings. The objective function used was minimum total power H_t and an additional condition of maximum load capacity. The analysis was based on a symmetrical load which limits the application of the results. The Powell programming method was used, without restrictions, after a preliminary use of penalty quadratic functions.

Sansinenea and Bueno[40] also adopted total power H_t as an objective function for the optimal design of hydrostatic journal bearings. Two optimisation programs were described, named OPTIM1 and OPTIM2. In the former, variables take discrete values according to the ISO number series. The Fibonacci technique was used for a one-dimensional search. The second program operates with continuous values. The search was conducted using the golden section search method. The difference between OPTIM1 and OPTIM2 can be found in the different algorithms employed for the one-dimensional optimisation along the direction of every design variable i.e. a process carried out with all the design variables fixed except one which is allowed to vary.

Computers have played an important role in the development of satisfactory design procedures including optimisation for externally pressurised fluid film journal bearings. Initially, computers were used to yield approximate solutions to the governing differential equation, e.g. Reynolds Equation, information then being incorporated into hand or graphical design procedures and design manuals. For example, Raimondi and Boyd[41] employed a computer to obtain approximate numerical solutions of Reynolds Equation and tabulated data for centrally-loaded bearings having arcs of 360°, 180°, 120° and 60° for L/D values of ∞, 1.0, 0.5 and 0.25. The solutions were achieved with great speed and reasonable accuracy.

Computer programs were later developed to yield design solutions to a particular problem by storing information produced by previous solutions of the governing equations, or by pursuing an iterative procedure in which the bearing parameters were calculated successively until a satisfactory match was achieved. Rippel[42] reviewed the utilisation of computers at this stage. The computer was mainly used as a design tool for the analysis of non-uniform film thickness distribution resulting from eccentricity, misalignment, and distortions, cavitation, and for either steady-state performance or dynamic response. With a computer, problems can be tackled, especially numerical problems which were very difficult to solve by other means. The development of computer programs was required on an individual basis. The operation of these programs was not flexible and far from user-friendly. There are many application examples of this type. For example, Singh, Sinhasan and Ghai[43] used the finite element method to analyse orifice-compensated hydrostatic journal bearings, Chen and Ho[44] undertook computer aided design of hydrostatic journal bearings including the shaft bending effect, and Lin, Aoyama, and Inasaki used a computer to simulate and analyse dynamic characteristics and stability of aerostatic journal bearings[45].

More recently computer programs were developed capable of yielding optimal bearing designs[40][42][46]~[47]. The underlying philosophy of this final step is interesting. Ever since the invention of the computer, designers have attempted to make the computer take on a greater part of the role of the bearing designer. The concept is simple, but the execution of the task is difficult and challenging[48]. Compared with the human mind, the computer has the merit of speed and efficiency but lacks versatility. A number of problems encountered in bearing design are not amenable to purely algorithmic solutions such as the establishment of the conceptual nature of the bearing system elements, selection of the bearing type and configuration and other design decision-making. In recent years, with the development of powerful techniques from AI and computer science, many workers in engineering design and tribology have undertaken the research on the development of higher level design aids based on the integration of AI technology with conventional design techniques[49]. The design of general purpose bearings is often suggested as a typical application for such design aids because of their essential role in machine operation. The symbolic computation ability of AI programs can accommodate qualitative design issues as well as quantitative issues. AI programs have the potential to provide the following:

- Help designers to understand and organise problem specifications.
- Determine the most suitable type of bearing.
- Help designers to identify limiting factors of design and to use numerical tools.
- Evaluate the compatibility of a proposed solution at various stages of design.
- Identify incompatibility in the proposed solution and provide suggestions.

Unfortunately, however, research publications in this domain still represent an early stage of development of the subject. There has not been any practical intelligent design support system for fluid film bearings developed yet even though research has been directed towards this end.

2.4 Design incorporated with AI

In 1986, Tallian[50] presented the idea of making tribological design decisions by using computerised databases incorporated with AI. He argued that databases are not a dead store of information, but rather, a methodical guide for a broad community of mechanical engineers, who need to apply tribological knowledge to specific, practical design or operating problems. He described the content and structural concept of a tribological design decision support system which considered a tribological problem as a design task. A simplified construction of the system is illustrated in Figure 2.2. It was suggested that the system could be used for tribological component selection, tribological design support, diagnosis of tribological failure, and decision support for tribological operations.

Ishii, Hamrock and Klinger[48] incorporated AI in the design of self-acting herringbone journal bearings. A numerical optimisation method was used which, generated values of bearing parameters based on the objective function of maximised radial load capacity of the bearing. AI was used for design compatibility analysis (DCA) which forms an outer, intelligent design loop that applies to the numerical optimisation. DCA identifies any incompatibility between the design requirements and the design solution, explains the flaw, and suggests modifications to improve the design. Both the numerical and AI programs were implemented on an IBM PC. The programs were written in Turbo-Prolog for DCA and Fortran for numerical optimisation. Ishii, Hamrock and Klinger also planned to extend the technique to the stability analysis of externally pressurised herringbone grooved journal bearings.

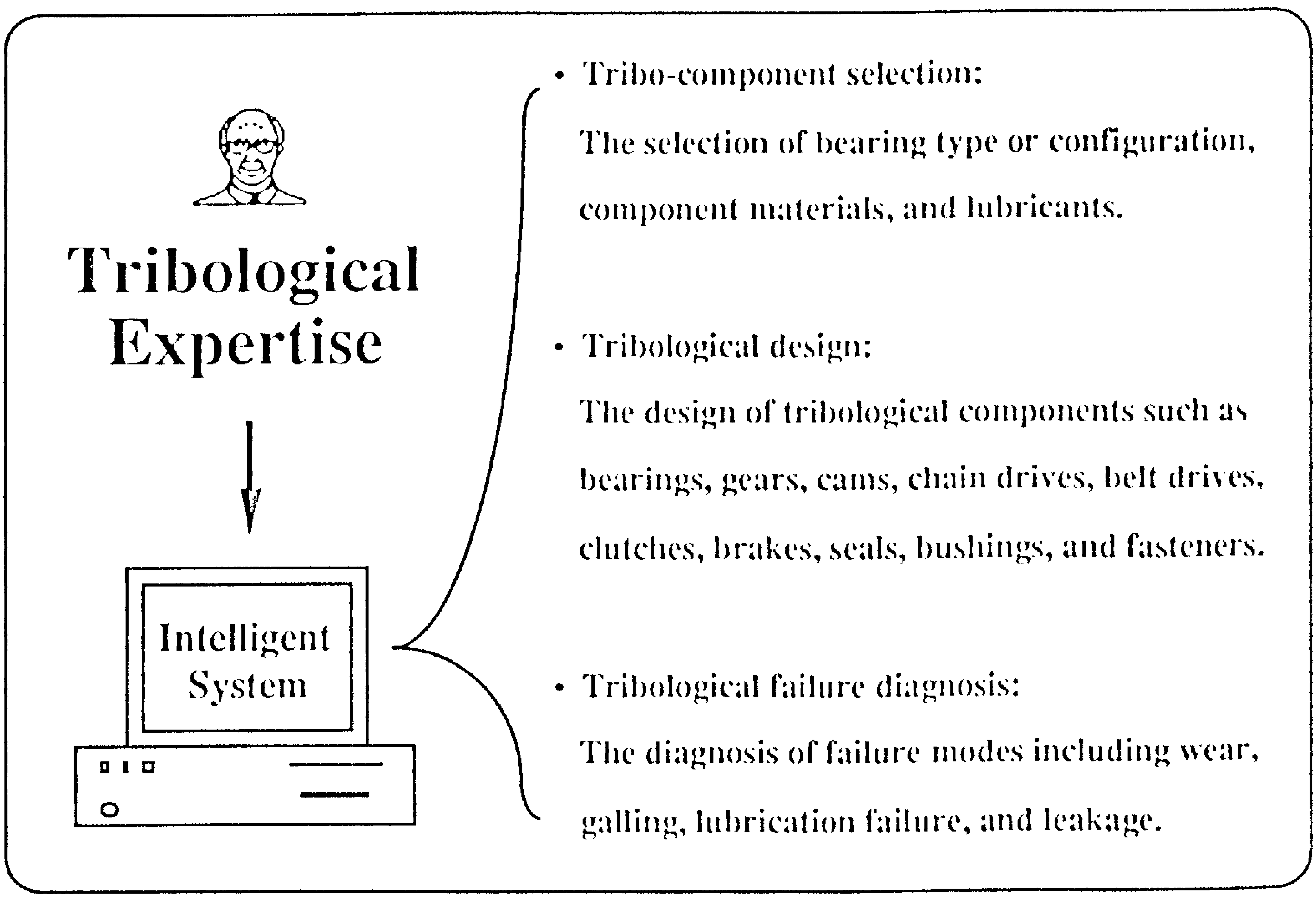


Figure 2.2 Simplified construction of a tribological decision support system

2.5 Conclusions

The design methods and different levels of design aids for externally pressurised fluid film journal bearings have been reviewed. It is concluded that the next significant step in bearing design is the development of a generalised design procedure for the design of both hydrostatic and aerostatic journal bearings.

The development of AI technology and powerful microcomputers provides a vehicle for developing computer-based decision support systems for bearing design. It is necessary and realistic to develop an intelligent decision support system for bearing design to bridge the gap between available knowledge and a broad community of designers.

Chapter 3 Formulation of Artificial Intelligence Techniques

3.1 Introduction

Minsky[51], one of the founders of the field of AI, described AI as the science of making machines (usually computer systems) do things that would require intelligence if done by humans. Unlike traditional computer programs, computer-based intelligent systems attempt to emulate the human thinking process and serve therefore as an extension of human creative and problem-solving abilities. The main classes of AI approach are expert systems, knowledge-based systems, hypermedia, fuzzy sets, and neural networks. However, these approaches involve different processes for knowledge representation, inference, and nonlinear association of information which are critical features of intelligent systems.

This chapter, is focused primarily on the foundations of expert systems and hypermedia techniques and considers the potential benefits and requirements for the application of these techniques to the development of intelligent design support systems. The two techniques selected for the project and the integration of these technologies are discussed in detail.

3.2 Expert systems

An expert system is a computer program that represents and reasons with knowledge of a specialist subject with a view to solving problems or giving advice[52]. An expert system may completely fulfil a function that normally requires human expertise, or it may play the role of an assistant to a human decision maker. The term knowledge-based system is sometimes used as a synonym for 'expert system' although, strictly speaking, the former is more general. An expert system is used to solve problems belonging to a specific domain, which is often helpful in reducing the complexity of a larger problem.

3.2.1 Architecture of an expert system

Figure 3.1 shows the structure of an expert system, which includes three basic components[53]:

- the knowledge base
- the inference engine
- the user interface

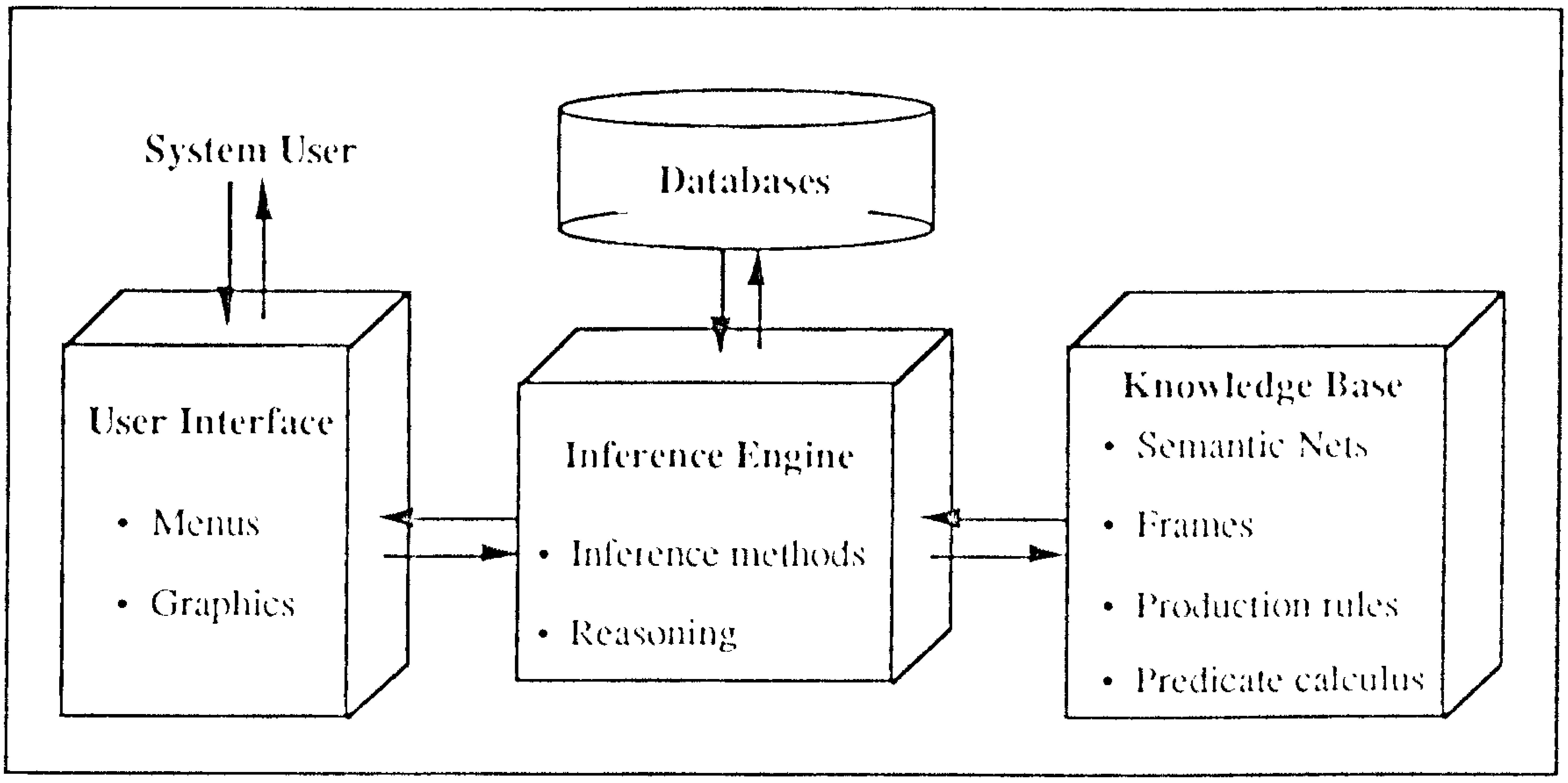


Figure 3.1 The block diagram of an expert system structure

The knowledge base houses the information used by the expert system in pursuit of a solution to a problem. A knowledge base is a step above a conventional database in that a knowledge base not only contains static data as in a database, but also contains relational information. Within a knowledge base, knowledge is most frequently represented by four models which are semantic networks, frames, production rules and predicate calculus.

The inference engine is the workhorse of an expert system. It consists of the processes that work the knowledge base, undertake analyses, form hypotheses, and audit the processes according to some strategy that emulates the expert's reasoning. Two types of reasoning strategy are forward chaining and backward chaining. Backward chaining inference begins with and focuses on the conclusions of rules. Backward chaining inference is best used in diagnostic, monitoring, and controlling applications. It is a goal-directed search that starts at the end solution and works backward towards the initial conditions. The task is to see whether the necessary and sufficient antecedents that satisfy the goal exist in the domain by applying inverse operations. In some senses, forward chaining inference is the opposite of backward chaining since it focuses on the premises of rules rather than their conclusions. Forward chaining inference is best used in "what-if" scenarios such as forecasting, designing and planning. The system begins with a fact and proceeds to search for a rule whose premise is verified by the fact. The conclusion is then added to working memory in pursuit of the solution.

The user interface allows a user to query the system, supply information and receive advice. Ideally, the user interface would provide the same form of communication facilities as provided by a human expert. In practice, the user interface has much reduced capability for understanding natural language and general knowledge. Graphic user interfaces provide a form of human-machine communication that has no direct analogue in human-human communication[54].

3.2.2 Knowledge representation

For each particular problem, the expert has a predefined structure or conceptual model of the domain, even though it may not be explicit. The selection of the knowledge representation model close to the expert's world lends itself to easier encoding of the knowledge. In addition, debugging and testing the expert system will not be so cumbersome with a knowledge representation model that naturally fits the expert's viewpoint.

Semantic networks are the most general representational structure and serve as the basis for other knowledge representations. Semantic networks themselves are rarely used to model the knowledge directly. The lack of definitive structural rules makes semantic networks inelegant to use, however, they need to be understood since they provide the theoretical underpinning for other representation methods such as frames and production rules. As an illustration of semantic nets, Figure 3.2 represents knowledge

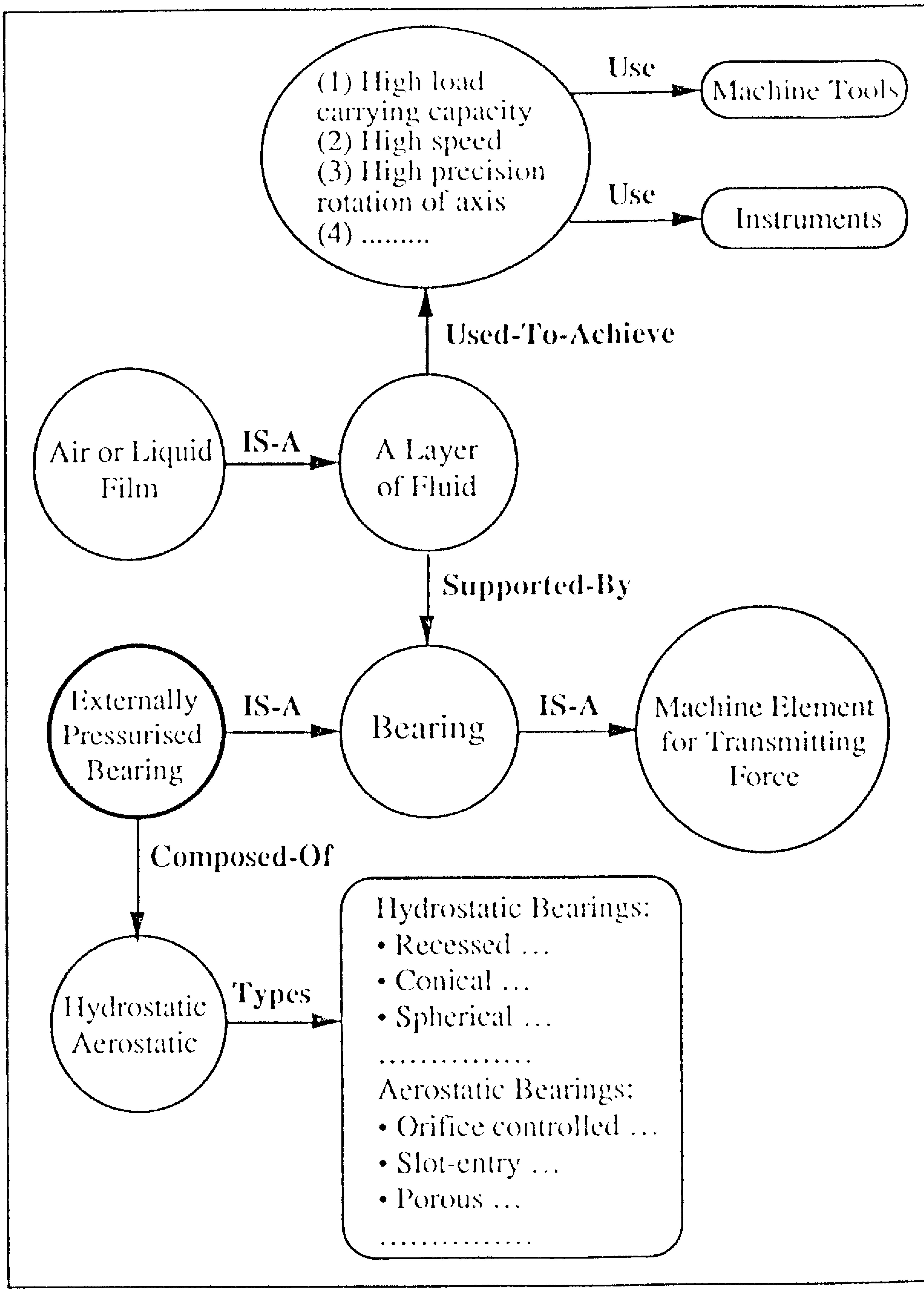


Figure 3.2 Semantic network of externally pressurised bearings

of externally pressurised bearings. The major advantage of semantic networks is flexibility through the ability to add, modify, or delete nodes and links where appropriate. The ability to inherit relationships from other nodes is another benefit of semantic networks. The main disadvantage of semantic networks is that there is no formal representation structure. No standard rules exist by which to define unique nodes or relationships.

Frames consist of a collection of slots that contain attributes to describe an object, a class of objects, a situation, an action, or an event. Frames provide a concise, structural representation of useful relations that capture the way an expert typically thinks about data in a knowledge base. Frames are an elaboration of semantic networks[55]. The primary advantage of frame representation is that it makes the knowledge base more concise and compact and therefore less time is required to search for specific information.

Production rules are conditional If-Then and If-Then-Else descriptions of a given situation or context of a problem. The If clause describes an object, situation, or position. If the If clause is true, the Then clause of the production rule is activated. If the production rule contains an Else clause and the If clause is false, the Else clause of the production rule is activated. Production rules provide a more formal representation structure for object-attribute-value (O-A-V) or attribute-value (A-V) semantic networks. Rule-based systems have several attractions such as modularity, uniformity and naturalness. However, rule-based systems have two primary disadvantages of rigidity and inefficiency.

Predicate calculus is an extension of propositional logic. It relies on the truth and rules of inference to represent symbols and their relationships to each other. For example, If A, Then B, and A exists, it is allowed to conclude B. Predicate calculus can be used not only to determine the truth or falsity of a statement, but also represent statements about specific objects or individuals. Predicate calculus has two major advantages of preciseness and modularity. Its primary disadvantage is that as the number of facts in the knowledge base increases, the number of ways to combine the facts to make inferences explodes exponentially. Predicate calculus is best used in domains of concise unified theories such as physics or chemistry.

In summary, Table 3.1 illustrates the characteristics of various knowledge representation models.

Characteristics / Models	Domain	Data	Structure	Control Strategy	Advantages	Disadvantages
Semantic Networks	Context Dependent	General	Hierarchical	Mixed	• Flexibility • Inheritance	• No formal representation structure.
Frames	Context Dependent	Unified, Concise	Hierarchical	Mixed	• Efficiency	• Not fully developed
Production Rules	Context Independent	Diffused	Uniform	Separable	• Modularity • Uniformity • Naturalness	• Rigid • Inefficient
Predicate Calculus	Context Independent	Unified, Concise	Uniform	Separable	• Preciseness • Modularity	• Not suitable for complex inference.

Table 3.1 Knowledge representation model characteristics

3.2.3 A general approach to developing expert systems

The development of expert systems may call for cooperation between a team of skilled people, as shown in Figure 3.3[53]. The domain expert typically provides the knowledge that will be used in the expert system. The knowledge is captured and encoded by the developer. Users should also be involved in developing the system, especially during the system specification of requirements, validation and evaluation, to ensure that the system works in a way that the user understands. Expert system building tools or environments have become higher level and easier to use, so that in many cases, experts can learn enough about the tools and techniques to build expert systems by themselves. Although the detailed architectures of specific systems vary across different knowledge domains, the methodology or approach to their development is basically similar in concept to that in the evolution of virtually any software.

It is suggested that the development of an expert system can be divided into six stages:

- Feasibility analysis: Identification and determination of the scope of the task and the reasonableness of the approach.
- Conceptual design: The conceptual structure of the system to be designed, along with

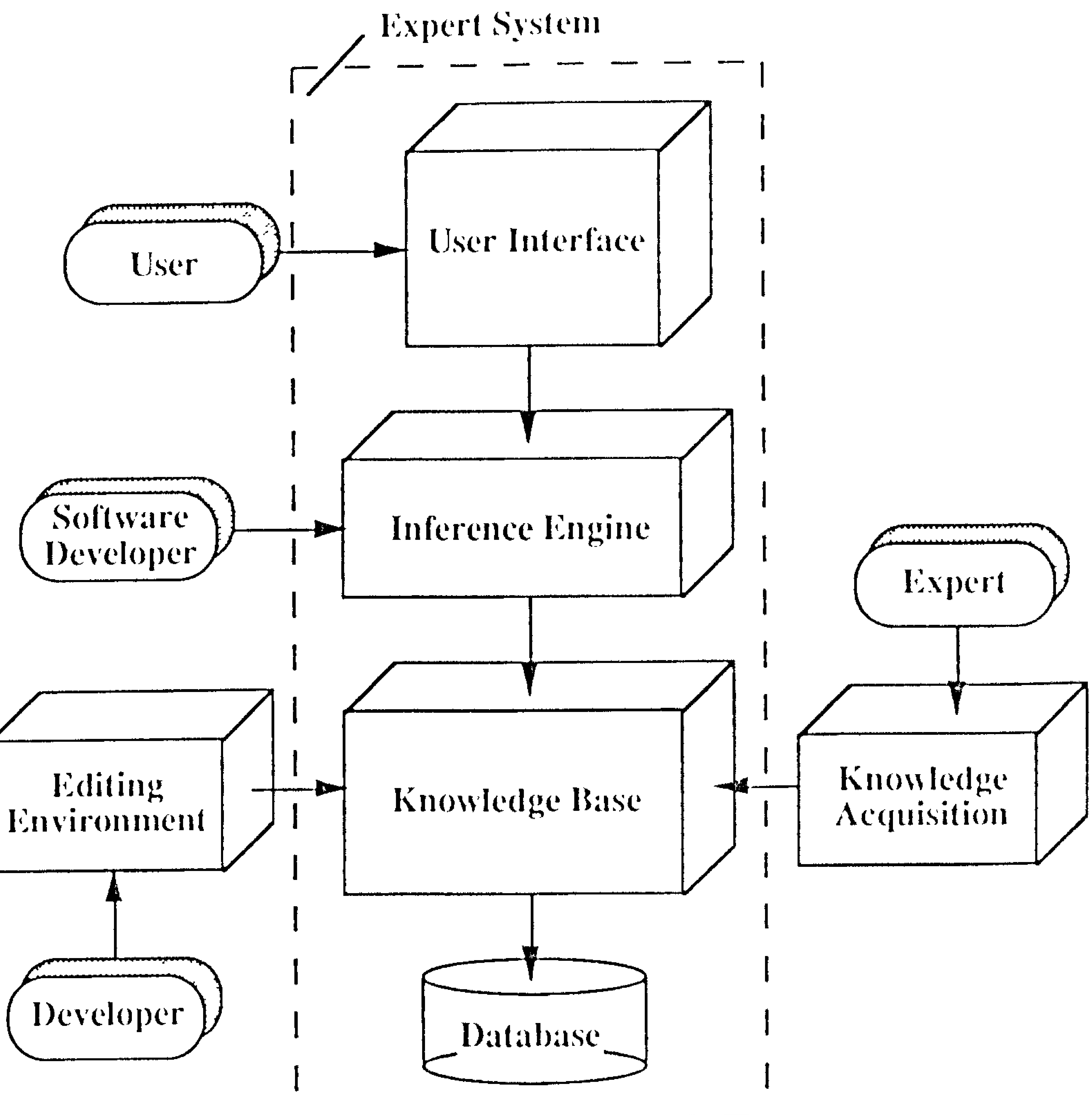


Figure 3.3 The expert system development team

a specification that describes the way in which the system will carry out the task.

- Knowledge acquisition: The knowledge required for performing the task is acquired from human experts, case histories, publications, et cetera.
- Knowledge representation: The knowledge is formalised and represented within the knowledge base so that it is executable by the inference engine.
- Validation and evaluation: User views, expert opinions, and operational criteria are used to determine whether the system has achieved an acceptable degree of success. The system is then carefully validated and refined.
- Maintenance: The process of evaluation and refinement may proceed throughout the life-cycle of a popular product. It entails the continual process of reviewing, modifying, and upgrading the knowledge base, hardware, and software due to the

dynamic environment of information, domain expansion and heuristic improvement.

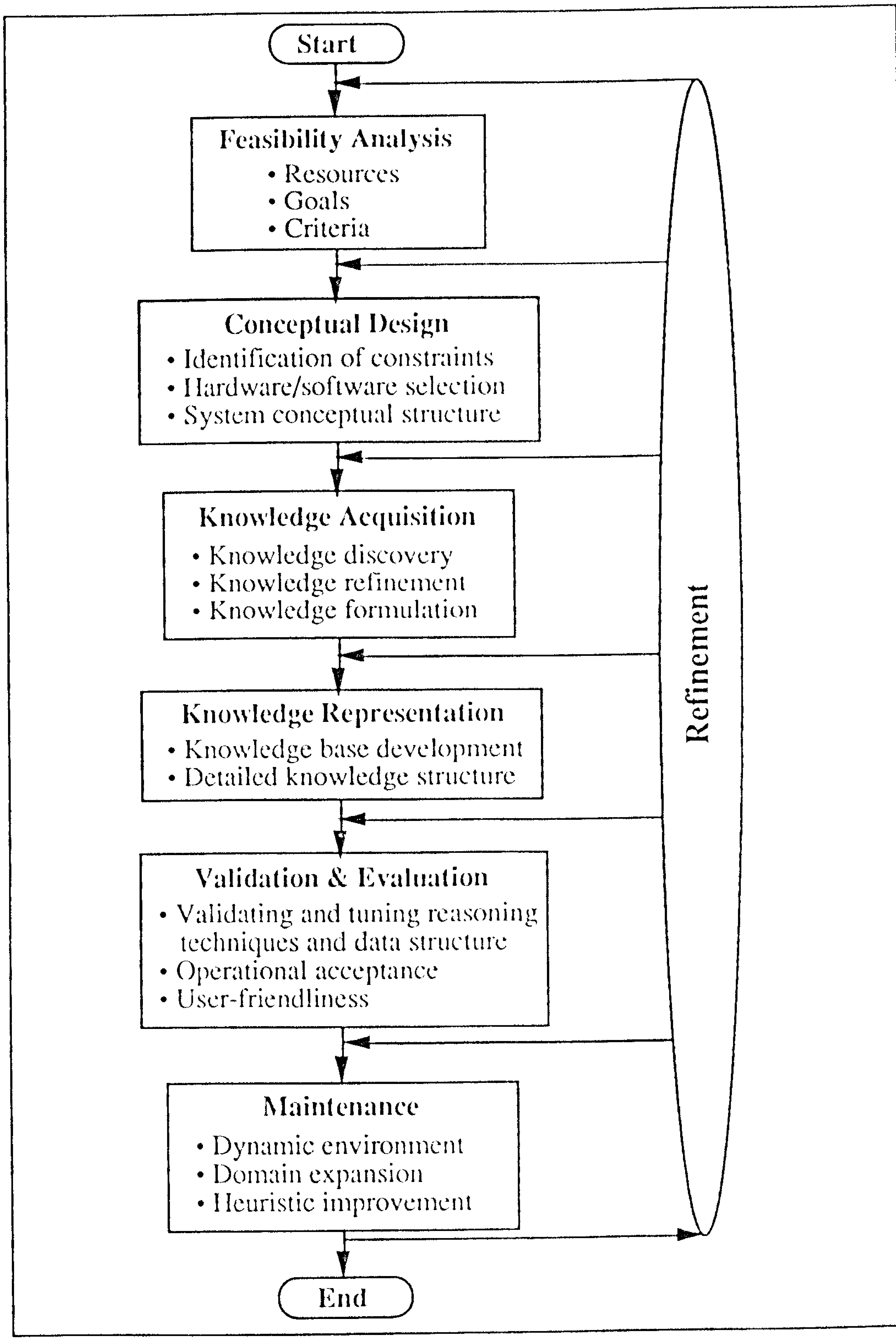


Figure 3.4 A flow chart of the system development process

Figure 3.4 illustrates a flow chart of the system development process described above. The flow chart provides, to some extent, an approach to the stages of building an expert system.

3.3 Hypermedia

Hypermedia is an information management tool that links text, graphics, sound, audio recordings, or other types of media in an organic and associative way[56]. In doing so, it allows users of a system to navigate information in a non-linear fashion. Users are free to progress through, or retrieve information from, the system by using non-linear pathways for which links have been established by the system designer. A non-linear pathway is a sequence established by moving freely or jumping within the information retrieval environment. Figure 3.5 illustrates a simplified view of a hypermedia structure

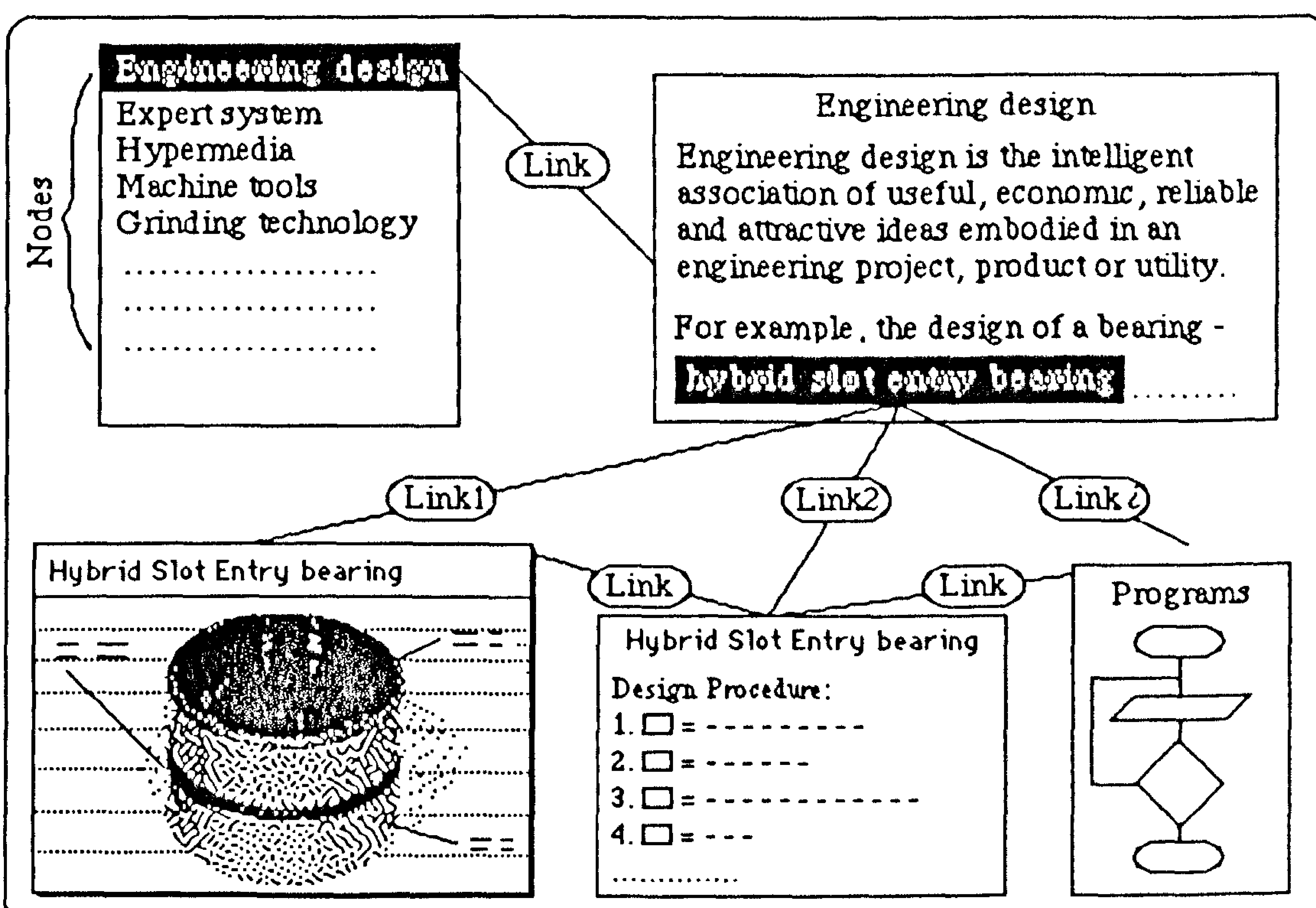


Figure 3.5 A simplified view of a hypermedia structure

describing an engineering subject. From the figure, it is found that hypermedia has two fundamental units which are nodes and links. A hypermedia system is basically a collection of nodes interconnected by links. The nodes can contain discrete blocks of information of text and graphics and other items like digital images, animation sequences, sound, and interactive video. A link is a machine-supported, direct connection between a specific source node and a destination node. A complete hypermedia system provides facilities for creating and editing nodes and links to form hypermedia documents, allowing any node to be connected to any other in a complex network.

'Hypertext' is a term coined by Nelson[57] in 1965. The technology is concerned with nonsequential reading and writing of textual materials using nodes and links. In recent years, however, distinctions between the terms hypertext and hypermedia have become somewhat blurred because many hypertext systems actually also include the possibility of working with graphics and various other media. In general, hypermedia is more inclusive. Hypertext and hypertext programs are usually taken as a framework and subset of hypermedia and hypermedia programs.

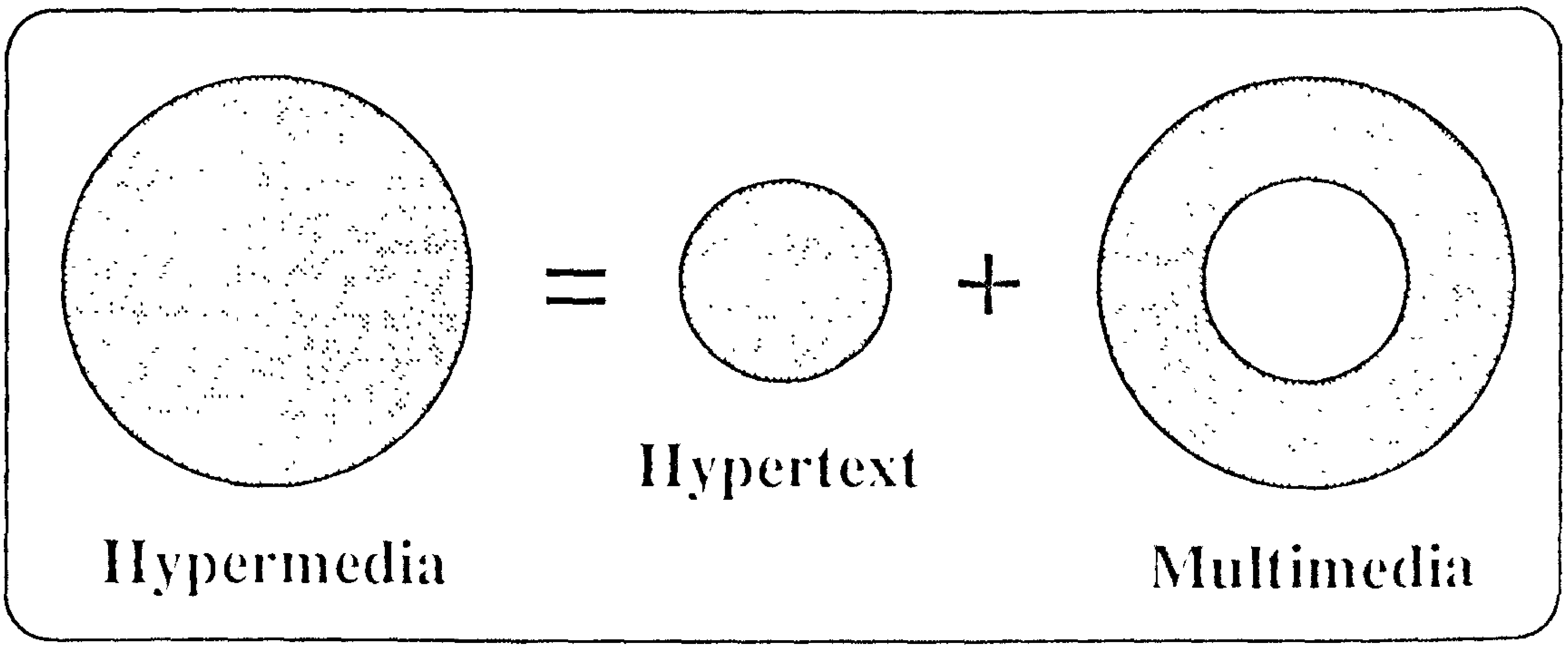


Figure 3.6 The relationship between hypertext, multimedia and hypermedia

Multimedia is often used as a synonym of hypermedia. However, it is clear from Figure 3.6 that a multimedia application is not necessarily a hypermedia application. Multimedia is concerned with the integration of various forms of media, but it is not necessary for it to have links or nodes as hypertext does. Hypermedia is the integration of the two approaches as illustrated in Figure 3.6[58]. Figure 3.6 shows the relationship between hypertext, multimedia and hypermedia.

3.3.1 Architecture of hypermedia systems

The architecture of a hypermedia system mainly refers to its organisation and navigation. Understanding the fundamentals of hypermedia organisation and notions of hypermedia navigation is very important for constructing a powerful hypermedia system.

3.3.1.1 Hypermedia organisation

Hypermedia systems are often based on one of three methods of organisation as illustrated in Figure 3.7[59]. These three methods are:

- Unstructured information, as in a random collection of 3-inch x 5-inch cards.
- A sequential collection of information units, as in a novel.
- A hierarchical collection of data or information, as in an organisational chart of a large corporation.

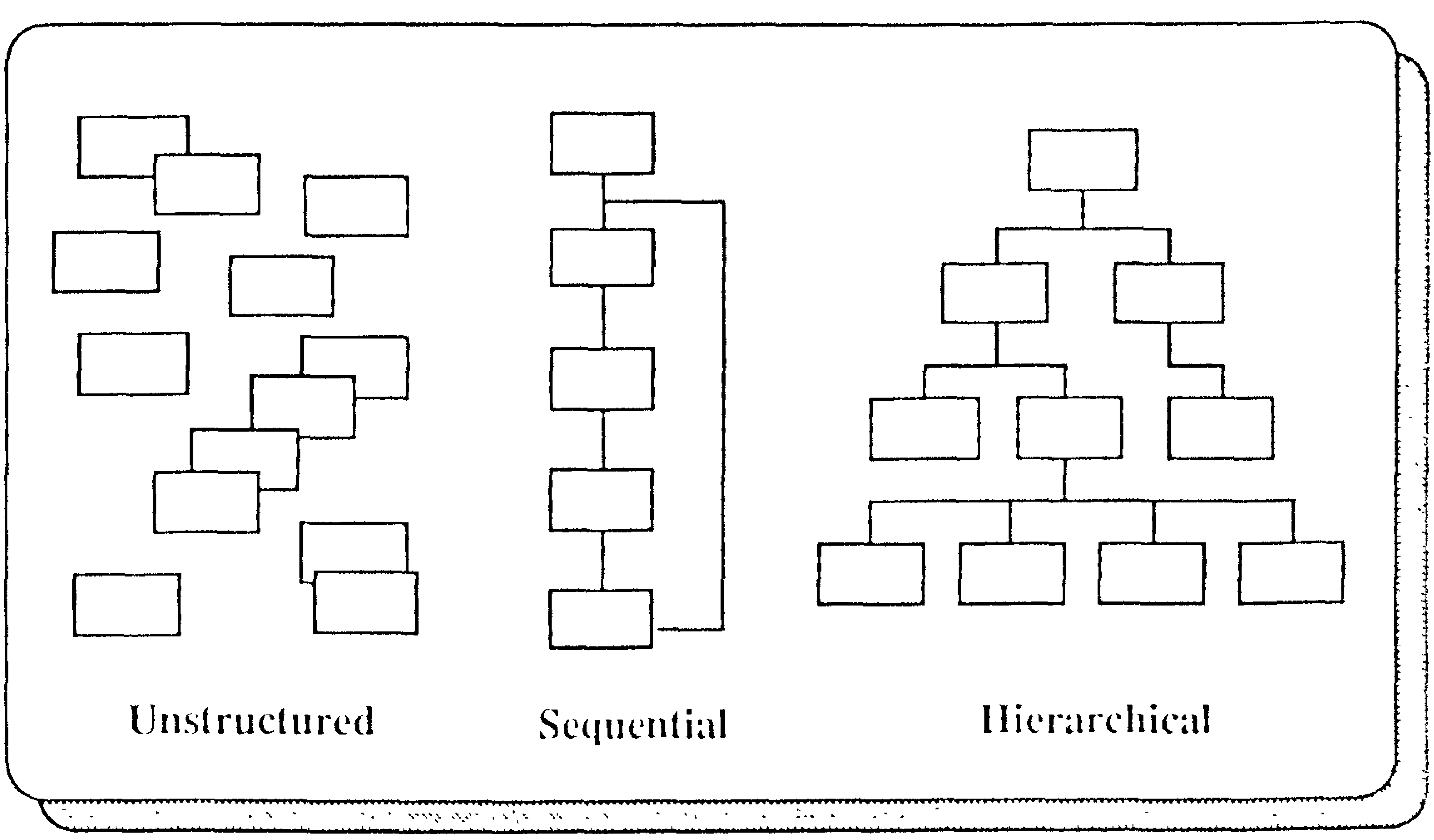


Figure 3.7 Types of hypermedia organisation

From Figure 3.7, it is found that a collection of information units, e.g., cards in a hypermedia document has an underlying order maintained by structural links. The order of cards in an unstructured hypermedia system can be arbitrary and quickly modified through standard sorting techniques. The order of cards in a sequential hypermedia system is usually static and used to represent information of a lengthy essay type. In a hierarchically structured hypermedia document, card order resembles a tree. In this case, the limbs of the tree declare primary structural relationships between cards.

3.3.1.2 Hypermedia navigation

The user's freedom, to navigate, browse and take part in discovery at will, is the most distinguishing feature of hypertext[60]. How a user navigates through a hypermedia system depends on how the system is indexed and what type of search/retrieval techniques it uses. Many hypermedia retrieval techniques use card identifiers, which can be listed alphabetically, indexed according to context, or organised hierarchically, sequentially, or relationally. Most hypermedia systems use a controlled vocabulary, where each hypermedia card is classified by one term and then maintained by an index of keyed terms. Some systems use aliasing techniques that allow links to be referenced by alternate names the user may supply at run-time. This technique improves a system's recall capability when single items within the hypermedia may be called by different names. In all cases, despite the labelling and indexing technique used, users still have the problem of navigating through the system and require more specialised devices such as browsers, filters, and bookmarks to deal with this problem.

Browsers come in many forms, and common implementations are card-reference lists, trees, and maps. Trees or maps offer a graphical view of the hypermedia system, marking the user's current location. These graphical aids to navigation reveal system structure and allow for direct access to information. Trees will often reveal hierarchical or relational structures, while maps give a sense of placement and proportion as well as overall structure and interconnection.

Filters act differently from browsers in helping to locate pertinent information by limiting the amount of retrieval information available or by narrowing the context for the search. Filters can take a variety of forms. For example, a system may be filtered according to time, allowing only access to information updated in the last day or two. Other filters might work from a list of key words or card-attributes and thereby limit the search range. The point of using a filter is to restrict the search pattern according to the user's needs.

A bookmark is a placeholder within the hypermedia system for one or more nodes that have already been accessed or called. With this device a system user can insert bookmarks that upon subsequent use of the system will serve as return reference points. Too many bookmarks, however, will result in a situation akin to highlighting too much material in a printed text, reducing the overall importance of the marked information.

3.3.2 Tools for developing hypermedia and hypermedia based systems

Hypermedia systems offer users intuitive, unstructured access to information. However, hypermedia developers cannot afford to take an overly intuitive approach to constructing hypermedia systems. Development tools are used to make it possible to develop systems quickly, qualitatively, and economically.

3.3.2.1 Major development tools

Early hypermedia system development tools like FRESS were mainframe-based[58]. Mainframes can support various hypermedia features. Almost all recent tools have been based on personal computers or workstations[61].

Table 3.2 lists some of the better known tools and provides a brief summary of the main features. It is impossible for the table to cover all the tools since new ones are constantly appearing. The tools list in the table are loosely classified according to their operating platforms such as IBM-PC, Macintosh and workstations. Among them, HyperCard has been emerging as a leading tool for building computer-based hypermedia applications.

Tools	Developer	Specifications
IBM PC:		
HyperPAD	Bright-Roberts	Features similar to HyperCard but does not support graphics. Easy to use and inexpensive.
ToolBook	Asymetrix Corporation	Full hypermedia features and runs with Windows 3.x.
HyperTies	University of Maryland	Basically a text based tool. A workstation version is available.
KnowledgePro	Knowledge Garden Inc.	An expert system shell with hypermedia functionality. Powerful but relatively expensive.
Macintosh computers:		
Guide	Kent University	Suitable for text documents but with full hypermedia features. Also available for workstations and IBM-PC compatibles.
HyperCard	Apple Computer Inc.	The most popular tool and supplied free with Macintosh computer.
Intermedia	Brown University	Full hypermedia features and inexpensive. A workstation version is available.
SuperCard	Silicon Beach Software Inc.	Owes much to HyperCard but with some advanced features such as colours and multiple windows.
Workstations:		
NoteCards	Xerox Palo Alto Research Center	Full hypermedia features and very expensive.
KMS	Carnegie-Mellon University	Text-based but with a limited graphic feature. A relatively expensive product.

Table 3.2 Some hypermedia system development tools

3.3.2.2 Criteria for tool selection

To date, there are hundreds of hypermedia development tools[58][61][62]. These tools vary significantly in their approaches to hypermedia feature representation, their ability to interface with external utilities such as video players, the way they integrate or implement intelligence, price and ease of development. The selection of a suitable tool is a critical step. The tool should fit the intended application as closely as possible.

Table 3.3 summarises the factors in selecting a hypermedia development tool with particular reference to the four functional levels listed.

The applications environment:	Information presentation Knowledge representation
The development environment:	Hypermedia implementation Artificial Intelligence development Information visualization and tracing Integration with existing data or programs
The user environment:	User interface design Navigation aids Custom report generation
The run-time environment:	Portability to other hardware platforms Cost, policy, and licensing of run-time systems

Table 3.3 Criteria and pertinent factors for a hypermedia system tool selection

3.3.3 Hardware support for hypermedia

Hypermedia needs to run on a computer and is therefore highly dependent on the available hardware technology. A hypermedia system may be seen as a platform; A combination of hardware and software elements that together support a multisensory information environment. Now that computers incorporate text and graphics as a matter of course, it is but another step to the inclusion of photographic images, sound, and motion video. As digital CD players, digital cameras, digital VCRs, and eventually, digital high-definition television take hold in consumer electronic markets, the previously segregated worlds of television, audio, and computing are predicted to become intermingled[63]. It is possible and even notable that these components will in the future become standard equipment in everyday personal computers which will be linked through national or even global computer networks. Figure 3.8, shows a typical hardware configuration for a hypermedia development system[64]. A special hardware problem is the large storage space needed for the multimedia images. For example, a single colour television image takes up 105 KB of storage, meaning that a minute of live video would take almost 150 MB memory. This makes it impossible to deliver hypermedia material with large sequences of video on traditional computer disks. Optical storage devices such as CD-ROM are a solution for this problem.

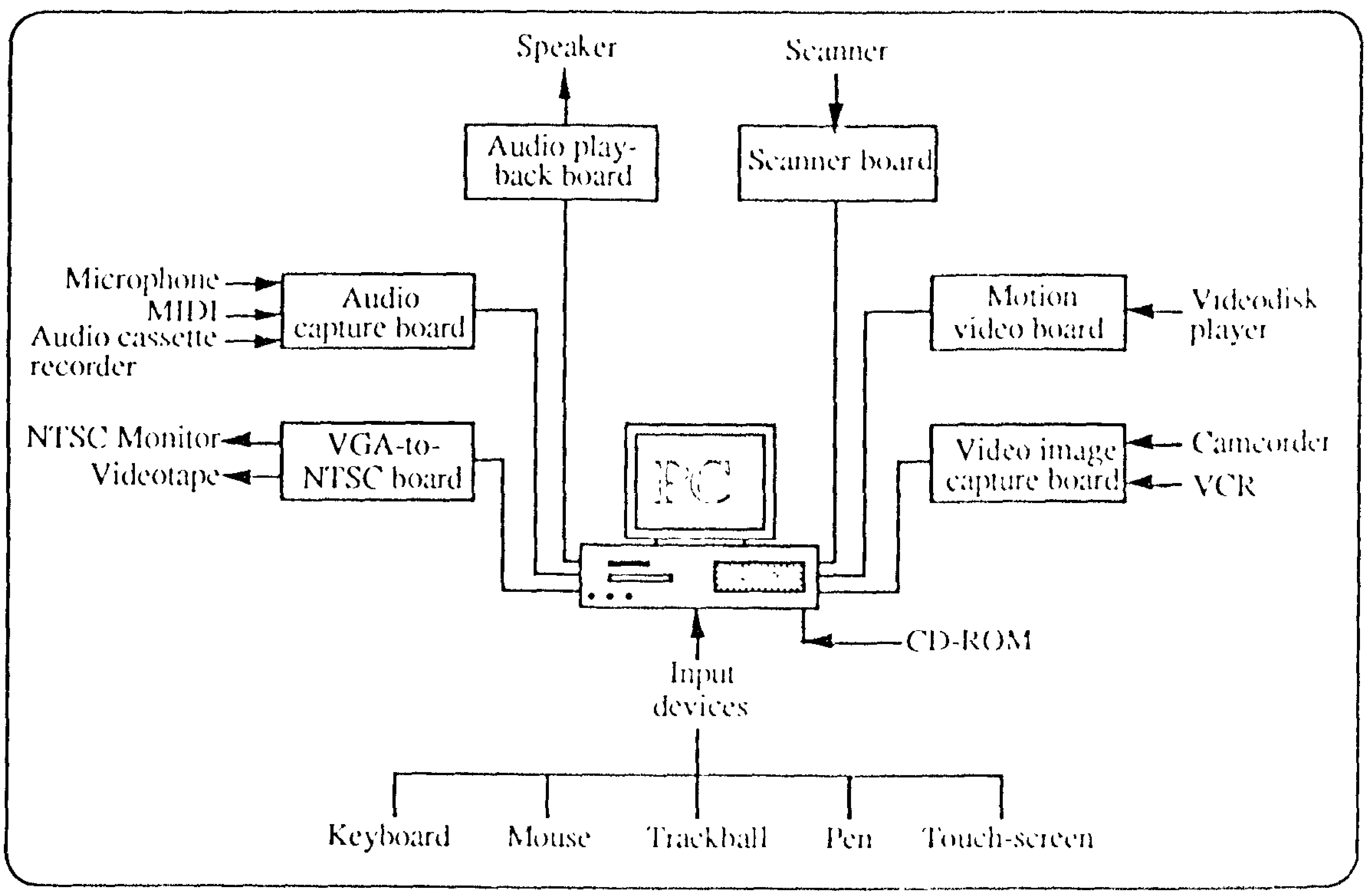


Figure 3.8 A typical hardware configuration for hypermedia

3.3.4 A general approach to developing hypermedia systems

There is still not a standard methodology or terminology for developing hypermedia applications. Developers use different methods to develop their systems depending on their skills and the particular requirements of the application. As a consequence, it is difficult to spread the use of hypermedia technology in a field of application. It is therefore considered to be essential to develop a methodology with particular reference to engineering applications.

A typical development team consists of a subject expert, a software developer, a graphic artist, a musician, and an evaluation expert[65]. The number of people involved can be reduced, of course, if any team member has the training needed to assume more than one role. There are three major stages in developing hypermedia systems, definition, development, and evaluation as illustrated in Figure 3.9. The focus of the definition stage is on developing, reviewing, editing, and finalising the content. The development stage mainly includes system framework design, selection of a suitable tool, design of system user interface, production of audio and visual materials employing various media, system programming or scripting, achievement of system prototype, and system validation. The evaluation stage includes peer review of the system, small group testing, and application field testing.

A methodology for developing a hypermedia system can be summarised as a set of steps. From the standpoint of hypermedia engineering, the steps are:

- Consult on the system requirements and specifications.
- Select the information to be transformed into hypermedia and choose a suitable hypermedia system development tool.
- Decompose the information into a definable organisational structure that is either based on the original organisational pattern or on a pattern determined by the system developer.
- Complete the final decomposition of the information into the smallest units that will be attached to each hypermedia node.
- Define the conceptual hypermedia links that provide knowledge representation within a semantic network.
- Define the links that govern program operation and the integration of multiple documents.
- Incorporating hypermedia devices such as browsers, filters, and bookmarks to facilitate user navigation.
- Integrate the system with AI, database or other advanced techniques.

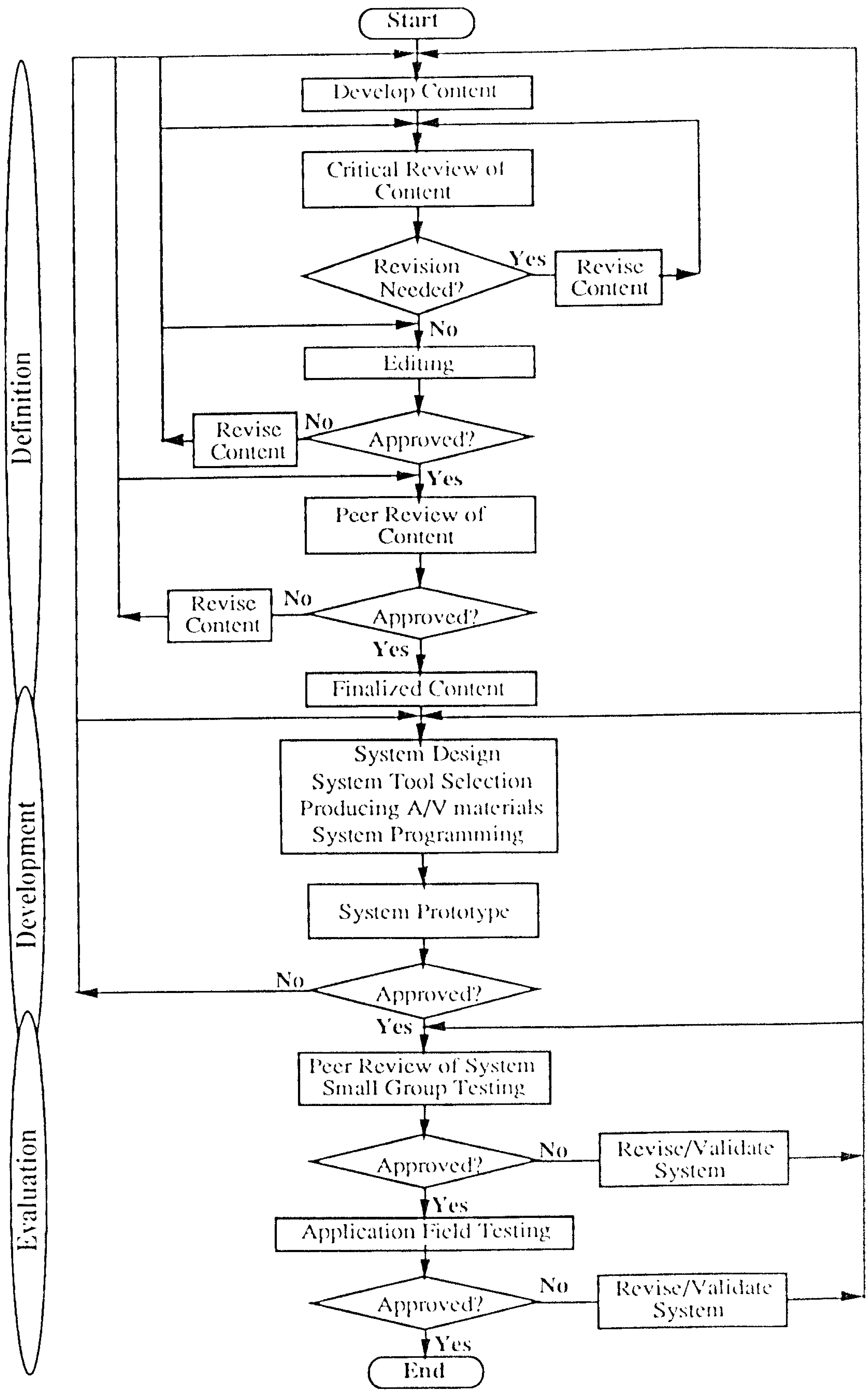


Figure 3.9 Flow chart for the development of a hypermedia system

- Validate, evaluate and refine the system.

3.4 Integration of different AI approaches

Of all the essential characteristics of an AI application system, knowledge representation, inference, and nonlinear association of information are the most critical. Unfortunately, no single information technology or application software can integrate these functions well. When integrated within a single application or used with existing programs, hypermedia and expert systems have the potential to offer a rich environment for creating software applications that can behave intelligently. They do so by combining the problem-solving, associative, and expressive powers of humans beings. Expert systems are particularly useful to augment problem solving or decision making. Hypermedia, in contrast, provides a vehicle for intuitive, nonlinear access to information and program navigation that realistically resembles intelligent behaviour.

When combined within an intelligent application system, expert systems and hypermedia technologies have a synergistic relationship, whereby their combined strength is more than the simple sum of their individual capabilities. For the synergy to occur, within the application program, the two technologies must be effectively linked. Most often hypermedia is employed as the base of the system and expert systems as components. Figure 3.10 shows the basic structure proposed for an intelligent hypermedia-based system. In this system, hypermedia serves as the backbone of the structure. Knowledge is stored in the hypermedia base in the form of text, graphics, sound, and other media. The artificial intelligence components may include expert systems, knowledge-based systems, intelligent databases and other components if required. These AI components are based on the hypermedia base and are particularly suitable for completing special functions such as design specification, design parameter computation, and design procedure analysis and control. The AI components can retrieve and make use of the knowledge in the hypermedia base. Intelligent hypermedia is becoming a major branch of both hypermedia technology and knowledge engineering[66]. Figure 3.11 shows the structured life cycle of an intelligent hypermedia application project.

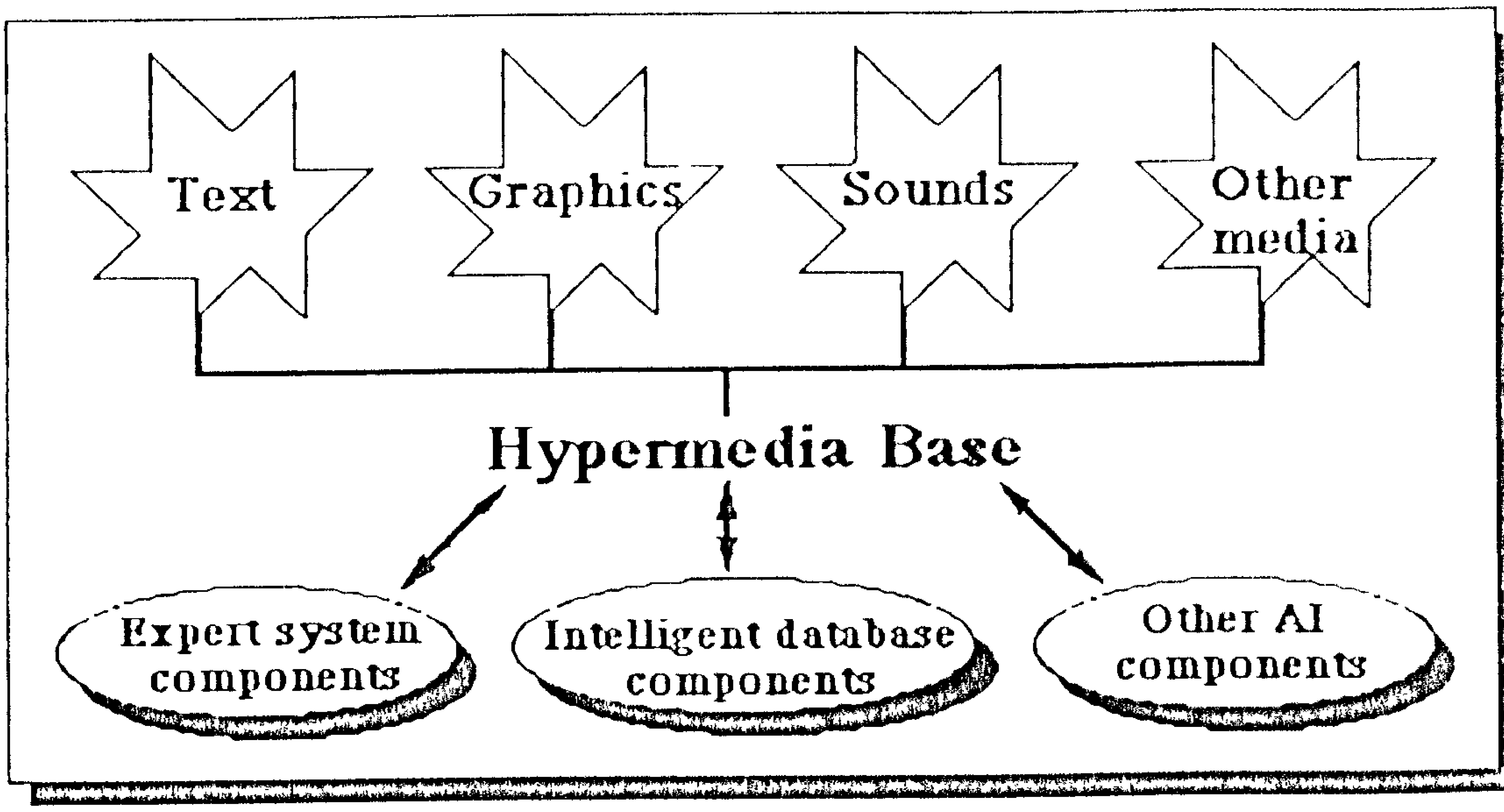


Figure 3.10 The structure of an intelligent hypermedia-based system

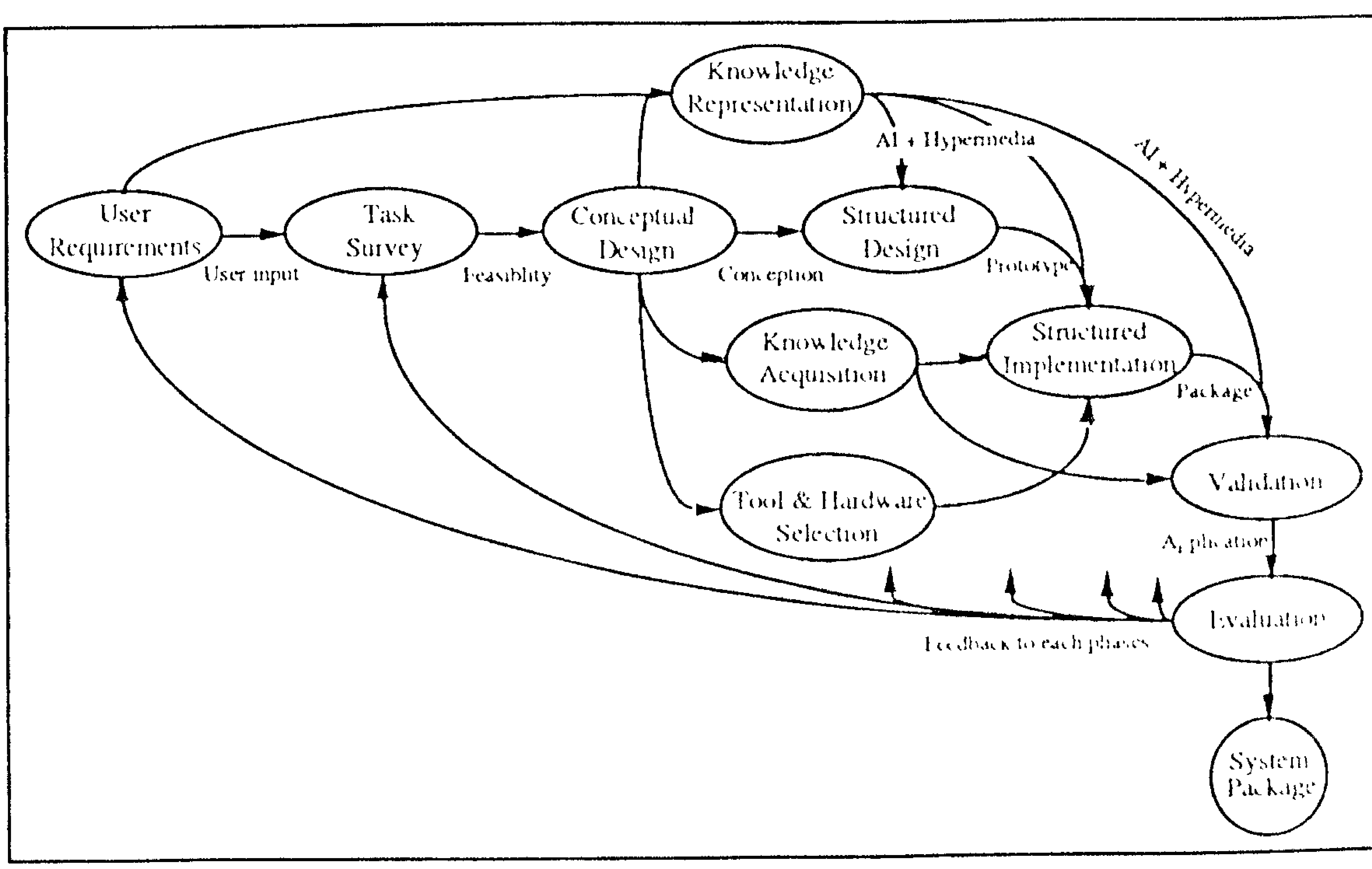


Figure 3.11 Structured life cycle of an intelligent hypermedia application project

Hypermedia-based intelligent systems have great potential because of the amount of knowledge that exists today in the form of raw text. Many developers argue that the next generation of AI-based applications will be 'text-based' rather than 'knowledge based' in the form of rules. Text based systems can be built more rapidly sidestepping much of the laborious knowledge-engineering process. Some hypermedia based intelligent systems have already been employed successfully in industry in recent years[67]. The author believes that hypermedia-based intelligent systems for engineering design and education will increasingly be employed in the near future.

Chapter 4 Development of a general design approach for externally pressurised journal bearings

4.1 Introduction

Many workers have produced design data for externally pressurised journal bearings. In the majority of cases, however, the design data were restricted to individual applications. It was therefore decided that a general design approach using available data was needed. The design method should provide a general methodological guide for bearing design covering all design phases. It should include various design aspects such as a design procedure, selection strategies for bearing type and configuration, flow control devices, bearing materials and manufacturing techniques, design optimisation and other design decision making within the procedure. It was also decided the development of the design approach should include its implementation on a computer. This chapter describes a view of the design process adopted as a framework for the later development of a design support system for externally pressurised journal bearings.

4.2 Design requirements and the design process

4.2.1 Design requirements

The foremost objective in the design of an externally pressurised journal bearing is usually one of the following[9]:

- To support a comparatively large load.
- To maintain a specified gap between the bearing surfaces.
- To minimise frictional losses.
- To maintain stable operation.

Design objectives are established by the constraints and environmental requirements imposed by the application. The bearing application will often decide the choice of lubricant, life required, acceptable cost, number of start-stop cycles, positioning precision needed, lubricant contaminants, bearing-alignment changes after start-up, loads, speeds, bearing ambient pressures, supply pressure and flow rate available

Design Requirements \ Design Elements	Lubricating Fluid	Bearing Configuration	Bearing Material	Auxiliary components		Production Techniques
				Flow Circuit	Control Devices	
High Temperature	*		*		◊	
Low Temperature	*		*		◊	
External Vibration	*	*			*	◊
Space	*	*		*		
Dirty or Dusty Conditions	*		*	*		◊
Wet and Humid Conditions	*		*	◊		◊
Running Costs	*			◊		
Production Costs	◊	◊	◊	◊	◊	*
Radial Motion Accuracy	*	◊			*	*
Stiffness in Relation to Size	*	*	◊		*	◊
Load Carrying Capacity in Relation to Size	*	*	◊	◊	*	◊
Damping	*				*	
High Speed	*					◊
Central Control	*	*			*	◊
Temperature Rise	*	◊			◊	◊
Durability	*	◊	*			
Maintenance		*		◊	◊	
Starting Torque	*					
Running Torque	*					
Running Noise	*			*		
Frequent Stop-starts	◊	*	◊			
External Dimension	*	*				
Ease of Design	*	*		◊	◊	◊
Ease of Manufacture	*	*	◊	◊	*	*
Availability of Standard Parts	*	*				
Prevention of Contamination of Surroundings and Products	*					

* -- Directly related
◊ -- Indirectly related

Table 4.1 Bearing design requirements and relationships to bearing features from the system, heat flow, system dynamics, size and location of restrictors. Conversely, design requirements may be imposed on the application system by the bearings. The assurance of compatibility of the bearing and the system design requires definition of the imposed bearing requirements and the bearing performance limitations. In the main, the design requirements can be classified according to their relationship to five elements of a bearing system. These elements of a bearing design are the lubricating fluid, the bearing configuration, bearing materials, auxiliary components such as flow control devices and circuits, and bearing production techniques. Table 4.1 lists possible design requirements for an externally pressurised bearing. Each design requirement may be directly or indirectly related to one or more of the five design elements. A bearing design study will usually start from a consideration of these design requirements. Load carrying capacity and operating speed are two requirements usually considered first although other requirements may become prominent factors in some specific applications. A successful design is the result of a balance in meeting various requirements. To achieve an optimum design, the design objectives have to be abstracted from the design requirements and then ideally transformed into objective functions. The optimum design search is undertaken based on objective functions. The design of an externally pressurised journal bearing involves a relatively large number of design parameters and for some configurations the computation may be complex. Computerised design solutions are therefore desirable and for a non-specialist might be considered a necessity.

4.2.2 The design process

The design data and drawings that form the visible record of a design do not completely disclose the underlying process by which the design was created. Understanding the design process and a designer's mental behaviour within the process has become an increasingly important part of the theory of design[68]. Assumptions concerning the designer's mental behaviour are essential for the development of an intelligent design support system.

(i) The feasibility study

After a designer decides to employ an externally pressurised journal bearing, it is necessary to commence with a feasibility study. The feasibility study involves the collection of information about the design requirements and about the constraints imposed on the design. Various factors must be considered such as the availability of a lubricant supply in terms of pressure and flow, the space available in the application system and the capability of manufacturing facilities. The feasibility study will include the presentation of several workable solutions. The feasibility study will include technical factors, economic factors and environmental acceptability.

(ii) Conceptual design

Conceptual design involves the generation and consideration of a number of ideas. The purpose of this phase is to attempt to avoid the situation where a simple better alternative is overlooked. Conceptual design involves the establishment of the conceptual nature of the bearing system elements including flow control devices and circuit. The process consists of a search for suitable solution principles and their combination into concept variants. For example, in this phase, a designer may decide to employ a hydrostatic bearing or an aerostatic bearing. In some cases the designer may decide to try a completely novel solution. This creates a problem for a highly structured design process. The designer needs to determine the possible bearing configurations which may be selected, the feeding type, bearing materials and possible production techniques. The designer should also establish approximate but essential values of main bearing parameters such as bearing diameter and length, clearance, load carrying capacity, stiffness, friction and pumping power consumption and supply pressure. At the conceptual design stage, a designer is encouraged to maintain an open mind to several design alternatives and continue evaluating these until sufficient information has been assembled to justify a decision.

(iii) Detail design

During detail design, the designer, starting from the established concept, determines the detailed production documents of all the individual parts. The precise values of bearing parameters, the detail design of the flow control device and the circuit system are finally specified, the bearing materials are specified, the technical and economic feasibility are re-checked and manufacturing drawings produced.

(iv) Production

The last phase is production which is an indispensable part of the engineering process. Production is the physical process by which materials are converted into a product. The variations in restrictor dimensions and clearance, resulting from manufacturing errors, have direct effects on the bearing performance. The designer must therefore take full account of manufacturing capability before detail design is completed. Shaft misalignment and distortion of a bearing reduce load carrying capacity and may increase power consumption. All of these effects need to be considered at an early stages.

In summary, Figure 4.1 illustrates the design process by a flow diagram. It must be stressed that the phases of the design process cannot always be clearly separated. Each phase influences the others and, as Figure 4.1 shows, overlap to a considerable extent. A conceptual decision may require a scale drawing for the purpose of deciding on possible layouts. Conversely, preliminary layout at the detail design phase may involve nothing more than rough sketches. Moreover, optimisation considerations may not only be made during the detail design period but also at the conceptual design phase. Such variations of the design process in no way detract from the value of the general methodology.

The design process may also be presented together with the design elements in a design matrix as shown in Figure 4.2. This gives a panoramic view of the design process and it should be possible to identify any design action as corresponding to some position in the matrix. Figure 4.2 also shows a simplified trajectory of designing a hydrostatic journal bearing with the matrix. Obviously, for a successful design, the trajectory is not unique and may be changed more or less depending on different designers. However, any design trajectory will be formed and defined within the design matrix.

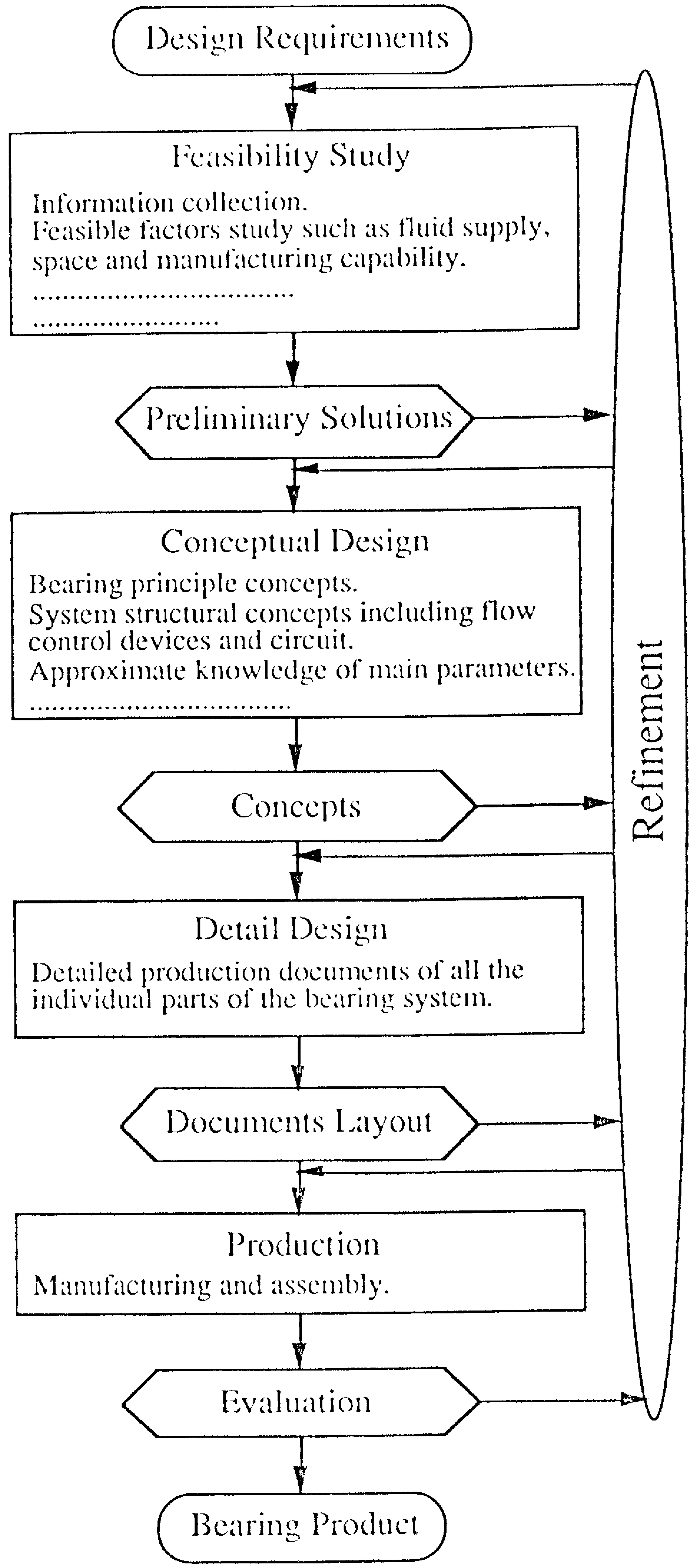


Figure 4.1 A flow diagram of the design process

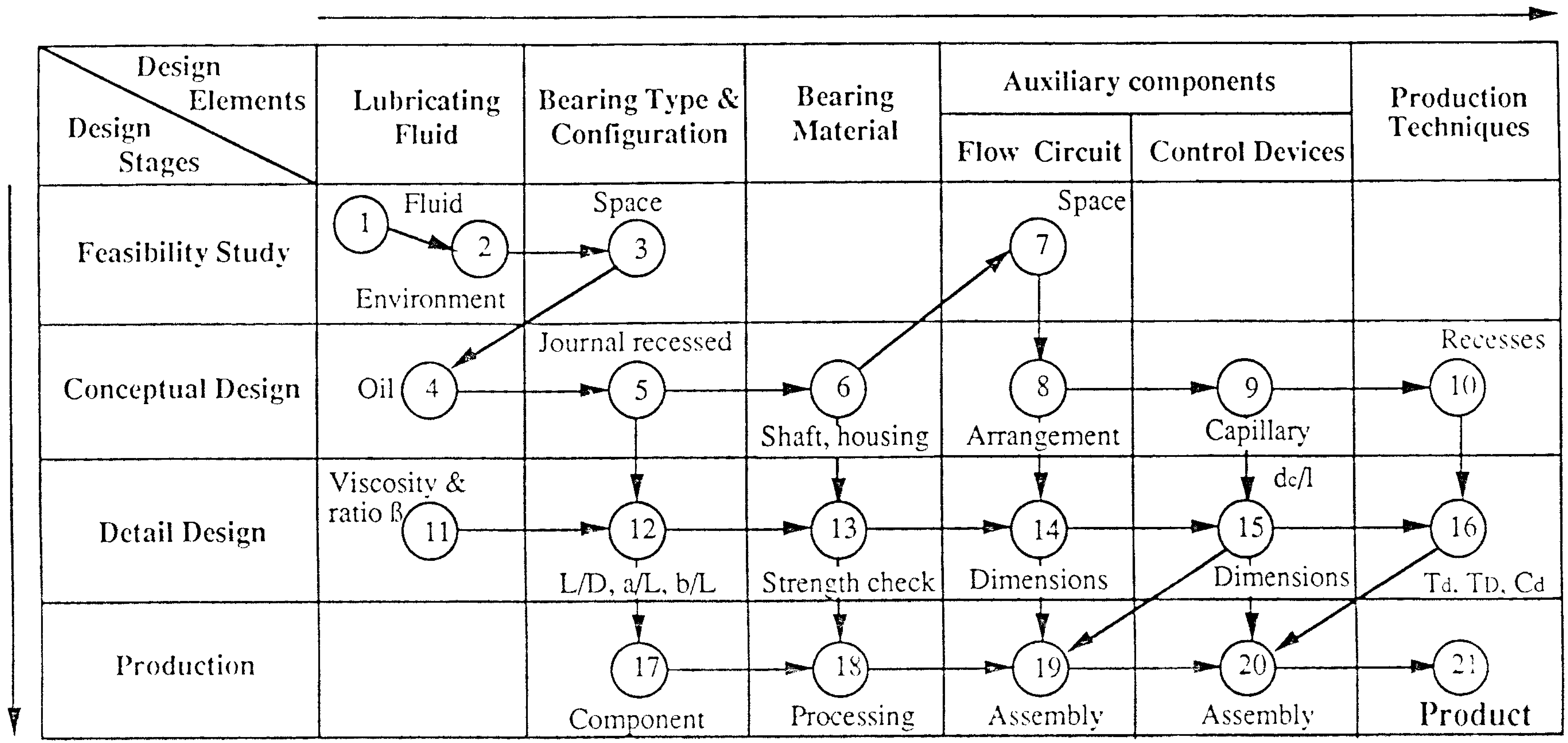


Figure 4.2 The design matrix with the design process and design elements

4.3 Selection strategies for the bearing

Bearing selection includes not only the bearing type itself, but also the configuration, the flow control devices, the materials and manufacturing techniques. The selection decisions are usually made or considered at an early stage of the design process. Selection decisions have direct effects on the achievement of a satisfactory design and the reliability of the total bearing system[34].

4.3.1 Bearing type and configuration selection

The range of journal bearings has been divided into seven classes as shown in Figure 4.3. The classes of bearing are rolling bearings, rubbing bearings, oil impregnated porous metal bearings, hydrodynamic bearings, hydrostatic bearings, self-acting air bearings and aerostatic bearings. As a designer starts the design process, he or she first has to make sure which type of bearing is suitable. The choice of bearing type will be appropriate for the particular application. The designer can then take further decisions such as the selection of the bearing configuration, flow control devices, bearing materials, and the bearing production techniques[35].

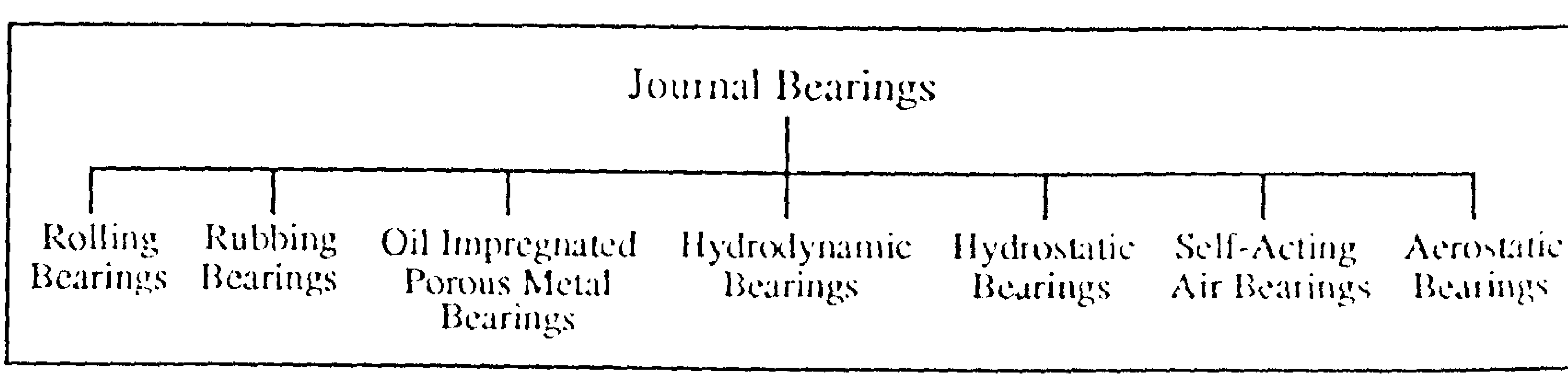


Figure 4.3 Journal bearings classification

The technique developed for selection of the bearing type is based on bearing operation factors which represent the design requirements. Operation factors for journal bearings are shown in Table 4.2, where a simplified rating system has been devised. For an operation factor x_i, there is a corresponding series of rating numbers, w_{i1}, w_{i2}, w_{i3}, w_{i4}, w_{i5}, w_{i6}, w_{i7}, which are individually associated with each of the seven types of bearings. The rating shows which type of bearing best satisfies the operation factor or

No	Bearing Types Y_j / Operation Factors X_i	Rolling Bearings	Rubbing Bearings	Oil Impregnated Porous Metal Bearings	Hydrodynamic Principles		Externally Pressurised	
					Hydrodynamic Liquid Bearings	Self-Acting Air Bearings	Aerostatic Bearings	Hydrostatic Bearings
1	High Temperature	**	***	*	*	****	****	*
2	Low Temperature	**	***	*	*	****	****	**
3	External Vibration	*	**	**	***	**	****	****
4	Limited Space	****	****	***	***	**	*	**
5	Dirty or Dusty Conditions	*	**	*	***	*	****	***
6	Wet and Humid Conditions	*	**	***	****	***	***	****
7	Running Costs	***	***	***	**	****	**	*
8	Production Costs	***	****	***	**	**	*	*
9	Radial Motion Accuracy	**	*	**	***	***	****	****
10	Stiffness in Relation to Size	***	**	*	***	**	***	****
11	Load Carrying Capacity in Relation to Size	***	**	*	***	**	***	****
12	Damping	*	**	**	***	*	***	****
13	High Speed	***	*	*	**	****	****	****
14	Central Control	**	*	*	**	***	****	****
15	Temperature Rise	**	*	**	**	****	****	***
16	Durability	***	**	**	***	**	****	****
17	Maintenance	***	****	***	**	**	*	*
18	Starting Torque	***	*	**	**	**	****	****
19	Running Torque	***	*	**	**	****	****	**
20	Running Noise	*	**	****	****	****	***	**
21	Frequent Stop-starts	****	****	***	**	*	****	****
22	External Dimension	****	****	****	**	***	*	**
23	Ease of Design	**	****	***	*	*	**	***
24	Ease of Manufacture	***	****	***	*	*	*	**
25	Availability of Standard Parts	****	**	***	*	#	#	#
26	Prevention of Contamination of Surroundings and Products	**	**	**	*	****	****	*
27	Vacuum	*	****	*	*	#	#	*
28	Frequent Change of Rotation Direction	****	****	**	**	*	****	****
29	Simplicity of Lubrication	***	****	****	*	****	***	**
30	Radiation	**	***	*	*	****	****	*

**** -- Excellent   *** -- Good   ** -- Normal   * -- Poor   # -- Not rated

Table 4.2 Comparison of bearing types

condition. Clearly, the operation factors $[X_i]$ (i = 1 to n) can be expanded or reduced depending on each specific application. For a specific application, each operation factor x_i is associated with a rating k_i which provides the weighting of the factor depending on the importance of the factor for a particular application. For instance, the factor for the spindle radial motion accuracy has a large weighting in designing bearings for an ultra-precision turning machine. Therefore, for the selection of the bearing type Y_j (j = 1 to

7), its rating result is

$$y_j = k_1 x_1 w_{1j} + k_2 x_2 w_{2j} + \ldots\ldots + k_{n-1} x_{n-1} w_{n-1,j} + k_n x_n w_{n,j}$$

so that

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \\ y_5 \\ y_6 \\ y_7 \end{bmatrix} = \begin{bmatrix} k_1 & k_2 & \ldots & k_{n-1} & k_n \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_{n-1} \\ x_n \end{bmatrix} \begin{bmatrix} w_{11} & w_{12} & w_{13} & w_{14} & w_{15} & w_{16} & w_{17} \\ w_{21} & w_{22} & w_{23} & w_{24} & w_{25} & w_{26} & w_{27} \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ w_{n-1,1} & w_{n-1,2} & w_{n-1,3} & w_{n-1,4} & w_{n-1,5} & w_{n-1,6} & w_{n-1,7} \\ w_{n,1} & w_{n,2} & w_{n,3} & w_{n,4} & w_{n,5} & w_{n,6} & w_{n,7} \end{bmatrix}$$

By comparing the rating results y_1, y_2, y_3, y_4, y_5, y_6, y_7, the bearing type Y_j (with corresponding y_j) is selected. Figure 4.4 shows the selection process with a selection

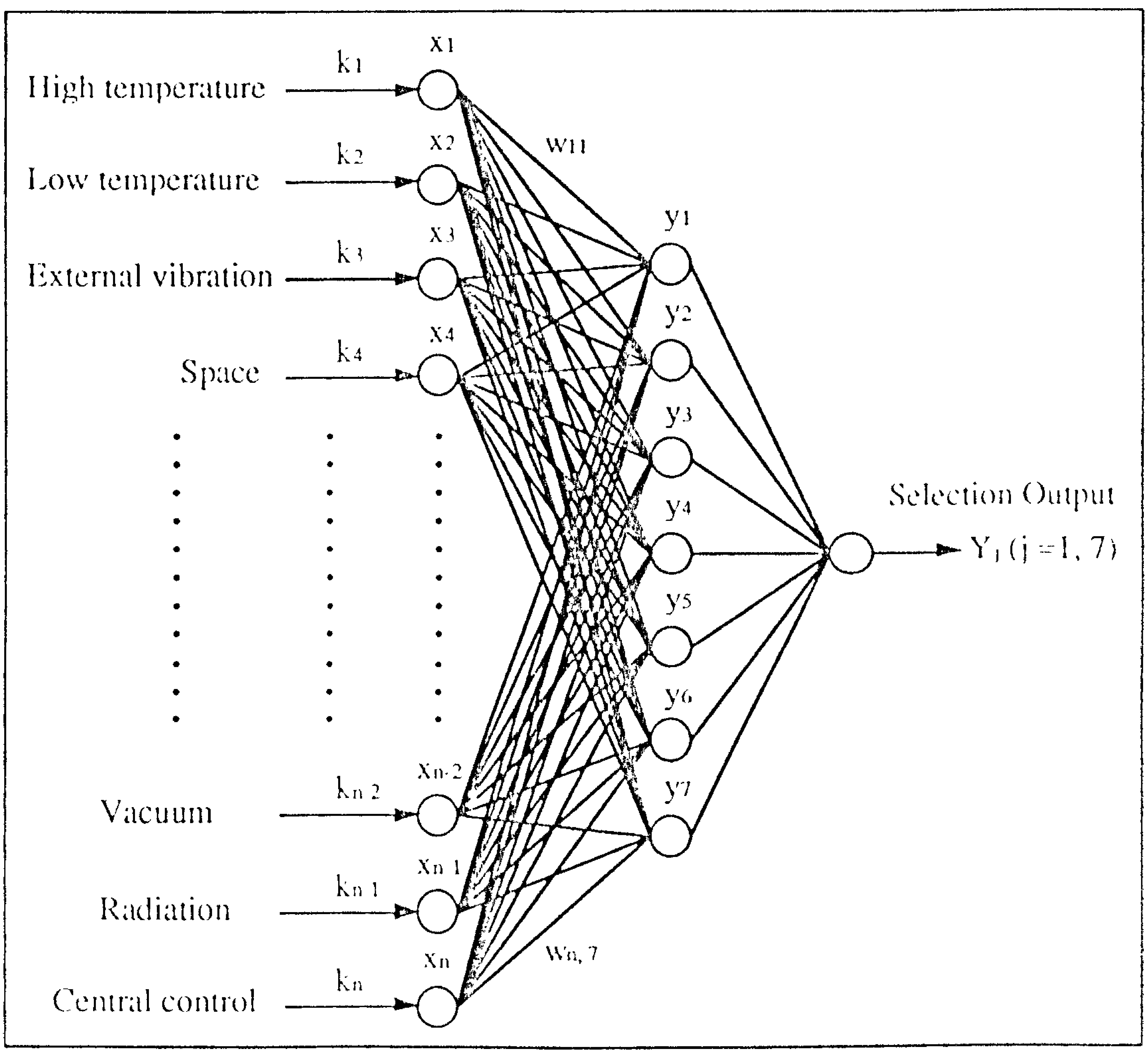


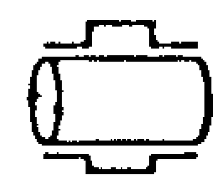
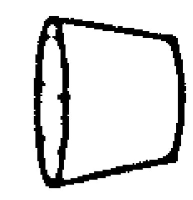
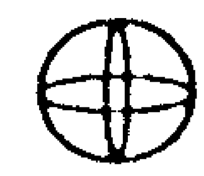
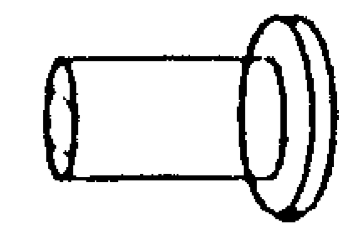
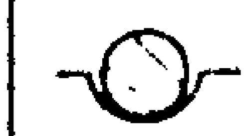
Figure 4.4 The selection network

network. The selection strategy can be implemented on the computer through a knowledge-based systems approach using production rules with weighting numbers. It can also be implemented by using other AI approaches such as neural networks or fuzzy sets theory.

Table 4.3 and Table 4.4 respectively shows operation factors for hydrostatic and aerostatic journal bearings with various configurations, where a simplified rating system has been used. The technique used for selection of bearing type can also be used for the selection of bearing configuration. However, it has to be stressed that each bearing configuration works together with a specific type of flow control device which is an indispensable element of an externally pressurised bearing system. Different types of flow control device have different effects on the bearing stiffness, load-carrying capacity and stability. The selection of the bearing configuration is therefore carried out in parallel with the selection of the flow control device.

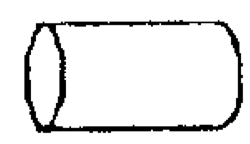
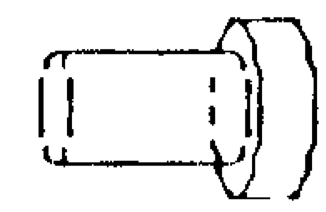
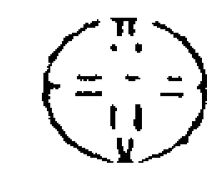
For Table 4.3 and Table 4.4, there are the following comments which need to stressed:

- Axial thrust bearings generally required for a journal bearing assembly are not included in these tables.
- The rating system provided for each table is a general guidance for the configuration selection with particular reference to the applications in machine tools. In particular cases other considerations may affect the final selection.
- The rating given to each bearing configuration of both hydrostatic and aerostatic bearings is under the condition of using flow control devices of the same type.
- The comparison of each bearing configuration of both hydrostatic and aerostatic bearings is under the condition of same journal diameters.
- The operation factor of self-aligning ability for a spindle support refers to how easily two bearings with the same configuration align themselves to support a spindle for a machine tools application.

No.	Configuration Types Y_j / Operation Factors X_i	Hydrostatic Journal Bearings: Recessed Cylindrical 	Hybrid Plain Journal 	Conical 	Spherical 	Combined Journal and Thrust (Yates) 	Partial Journal 
1	Pumping Power	**	***	***	**	****	*
2	High-Speed Load-Carrying Capacity	***	****	**	**	***	***
3	Self-Aligning Ability for a Spindle Support	**	**	****	****	**	#
4	Ease of Adjusting Clearance on Assembly	*	*	****	*	*	**
5	Ease of Assembly and Installation	***	**	**	*	***	****
6	Axial Space	**	****	***	***	**	*
7	Radial Space	***	****	**	**	***	*
8	Frequent Changes of Rotation Direction	****	****	****	****	****	#
9	Ease of Manufacture	**	***	**	*	***	****
10	Ease of Design	**	**	**	*	**	****
11	Reliability	***	***	***	**	****	*
12	Production Costs	**	***	**	*	***	****
13	Maintainability	**	***	**	*	**	****
14	Stiffness in Axial Direction	#	#	***	**	****	#
15	Stiffness in Radial Direction	****	****	**	**	***	**
16	Endure External Vibration	****	***	**	**	***	*
17	Maintain the Journal Position in Radial Direction	***	***	****	****	***	*
18	Maintain the Journal Position in Axial Direction	#	#	****	****	***	#
19	Carrying High Loads in the Axial Direction	#	#	****	**	****	#
20	Carrying High Loads in the Radial Direction	****	****	**	**	***	**
21	Economy of Flow Rate, Power and Number of Parts	**	**	****	***	****	*
22	External Size for a Defined Shaft Diameter	**	****	**	*	**	*
23	Combinations of Axial and Radial Load Carrying Capacity	#	#	***	**	****	#

**** -- Excellent   *** -- Good   ** -- Normal   * -- Poor   # -- Not rated

Table 4.3 Comparison of hydrostatic bearing configurations

No.	Configuration Types Y_j / Operation Factors X_i	Aerostatic Journal Bearings			
		Cylindrical Journal 	Cylindrical Journal and Thrust 	Conical Journal 	Spherical 
1	Load Carrying Capacity in Axial Direction	#	****	***	***
2	Load Carrying Capacity in Radial Direction	****	***	**	**
3	Positioning Accuracy in Axial Direction	#	***	****	****
4	Positioning Accuracy for Angular Direction	*	****	****	***
5	Positioning Accuracy in Radial Direction	***	**	****	****
6	Stiffness in Radial Direction	****	***	**	**
7	Stiffness in Axial Direction	*	****	***	**
8	Production Costs	****	***	**	*
9	Ease of Design	****	***	***	**
10	Ease of Manufacture	****	***	***	*
11	Ease of Maintenance	****	***	**	**
12	Self-Aligning Ability for a Spindle Support	*	*	**	****
13	Combined Axial and Radial Load Carrying Ability	#	****	***	**
14	Economy of Flow Rate, Power and Numbers of Parts	*	***	****	***
15	Endure External Vibration	**	****	**	**
16	External Size for Forced Journal Diameter	****	***	**	**
17	Damping and Stability	**	****	***	***

**** -- Excellent   *** -- Good   ** -- Normal   * -- Poor

Table 4.4 Comparison of aerostatic bearing configurations

4.3.2 Flow control device selection

Basically, any type of restrictor can be employed as a flow control device in an externally pressurised bearing system, if load on the bearing never changes. But if stiffness, or load and flow variations, are part of the problem, choice of the proper flow control device or restrictor becomes critical[69].

Table 4.5 shows the characteristics of restrictors used in hydrostatic bearing systems.

Characteristics / Control Type	Advantages	Disadvantages
Capillary restrictors	• Manufacturing simplicity. • Bearing load and stiffness are independent of fluid viscosity and hence temperature rise. • They endow the bearing with the greatest tolerance to manufacturing variances on bearing clearance.	• Stiffness with capillary and slot-entry restrictors is less than with other forms of external restrictors but more linear. • Possible space problem due to length requirement.
Orifice restrictors	• Orifices are more compact than capillaries and give fractionally greater stiffness.	• Orifices are more prone to silting and clogging and this changes the orifice characteristics.
Constant flow control	• Better stiffness and load carrying capacity than other three types of restrictors considered.	• It is expensive for multiple-pad bearings. • The maximum bearing pressure is limited. Limitations of high-pressure pump and large pressure-drop across a valve.
Slot-entry restrictors	• Bearings with this type of restrictor can have low L/D ratio and small sizes. • Compact bearing assembly. • Bearing load and stiffness are independent of fluid viscosity and hence temperature rise.	• Stiffness with slot-entry restrictor and capillary is less than with other forms of external restrictors but more linear.

Table 4.5 Comparison of restrictors used in hydrostatic bearing systems

There are also some other flow control methods used in hydrostatic bearings such as pressure-sensing valves, reference bearings, inherent compensation and hole entry[23]. However, these flow control methods require special design support and were considered to be too complex for inclusion.

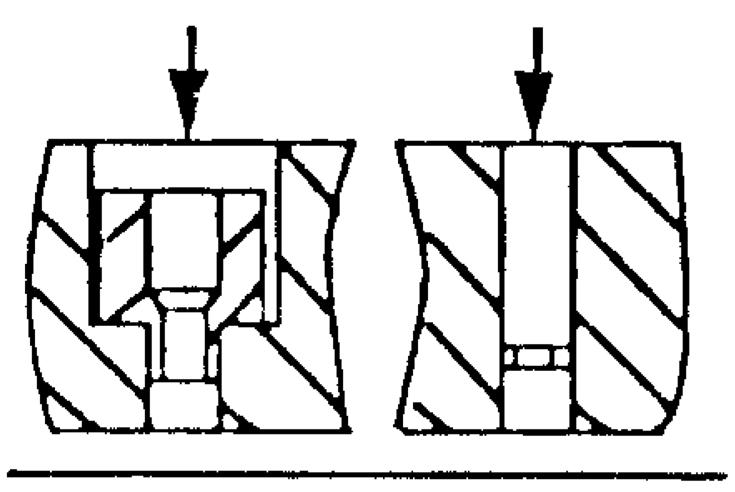
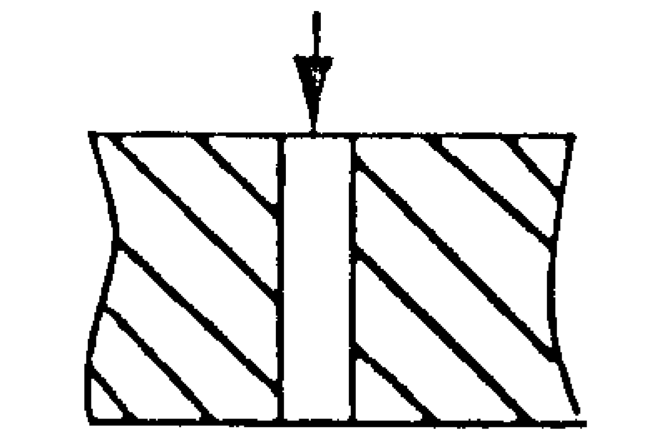
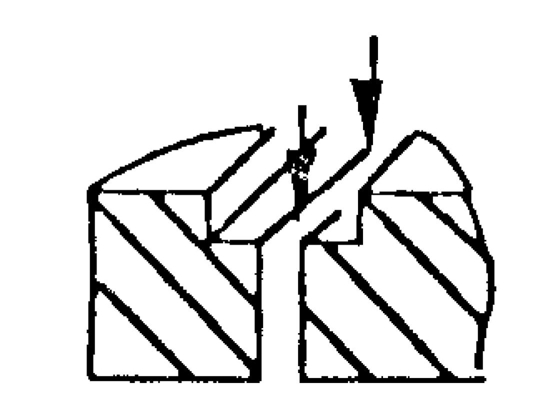
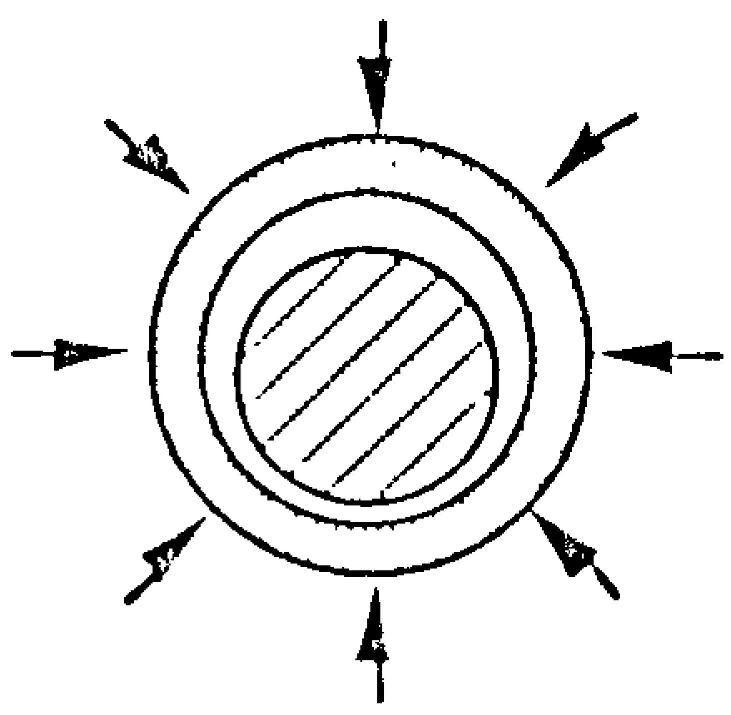
Characteristics / Restrictor Type	Advantages	Disadvantages
Pocketed orifice 	• This is the most common geometry and provides for the highest stiffness.	• The pocket can lead to 'pneumatic hammer'. • Manufacturing more difficult. • Prone to blockage
Annular orifice 	• It is free from pneumatic hammer and usually the simplest form of bearing construction.	• Load carrying capacity and stiffness are 33% lower than when using pocketed orifice.
Slot 	• Bearings with this type of restrictors can have low L/D ratio and small sizes. • No dispersion losses like that associated with orifices[70]. • Free from pneumatic hammer.	• The slots are prone to silting and clogging.
Porous surface 	• Because of the wide distribution of the feeding, high load carrying capacity can be achieved. • Structure simple.	• Large clearance. • Unpredictable permeability. • The pressure drop characteristics are a complex function of material dimensions and fluid properties.

Table 4.6 Comparison of restrictors used in aerostatic bearing systems

In summary, the main factors affecting the choice of restrictor type are:

- Stiffness
- Manufacturing simplicity
- External dimensions
- Stability

• Costs

Table 4.6 shows the characteristics of restrictors used in aerostatic bearing systems. The factors affecting the type of the restrictor for aerostatic bearings are mostly the same as for hydrostatic bearings. The manufacturing factor becomes more important in the choice of aerostatic bearing restrictors because the bearing has a smaller diametral clearance and hence a smaller manufacturing tolerance. In practice, the selection of the type of restrictor is undertaken in parallel with the bearing configuration because both have the same weight on the bearing performance and both are essential elements of a bearing system.

4.3.3 Materials selection

There may be periods when lubrication is not maintained in externally pressurised journal bearings due to one of the following reasons:

- Overload,
- Lubricant starvation,
- Contamination of lubricant,
- Handling of the equipment with lubricating fluid supply disconnected.

When these undesirable conditions exist, metal to metal contact may occur. Thus appropriate materials must be chosen for the shaft and bearing to minimise possible damage to the contacting surfaces and hence the bearing system.

The criteria generally considered in the selection of bearing materials are listed in Figure 4.5. In principle, each of the criteria from the figure can be applied to the choice of bearing bush material, as well as to the choice of shaft material. An appropriate selection decision depends on a trade-off between these criteria depending on each specific application. In aerostatic bearings, for example, all component parts which are in contact with the supply air and exhaust air must be corrosion resistant. The damp air will cause corrosion of unsuitable materials and therefore the failure of an aerostatic bearing. Stainless steels are ideally suited for use in structural parts in contact with damp air. However, stainless steel has a low thermal conductivity and poor machinability which have to be considered for some applications. Typical examples of a good bearing material for high accuracy and low wear include lead bronzes, phosphor bronzes and silicon nitride. Suitable materials for a shaft or journal include nitrided steels, stainless steels, chromium and tungsten carbide coated materials[35].

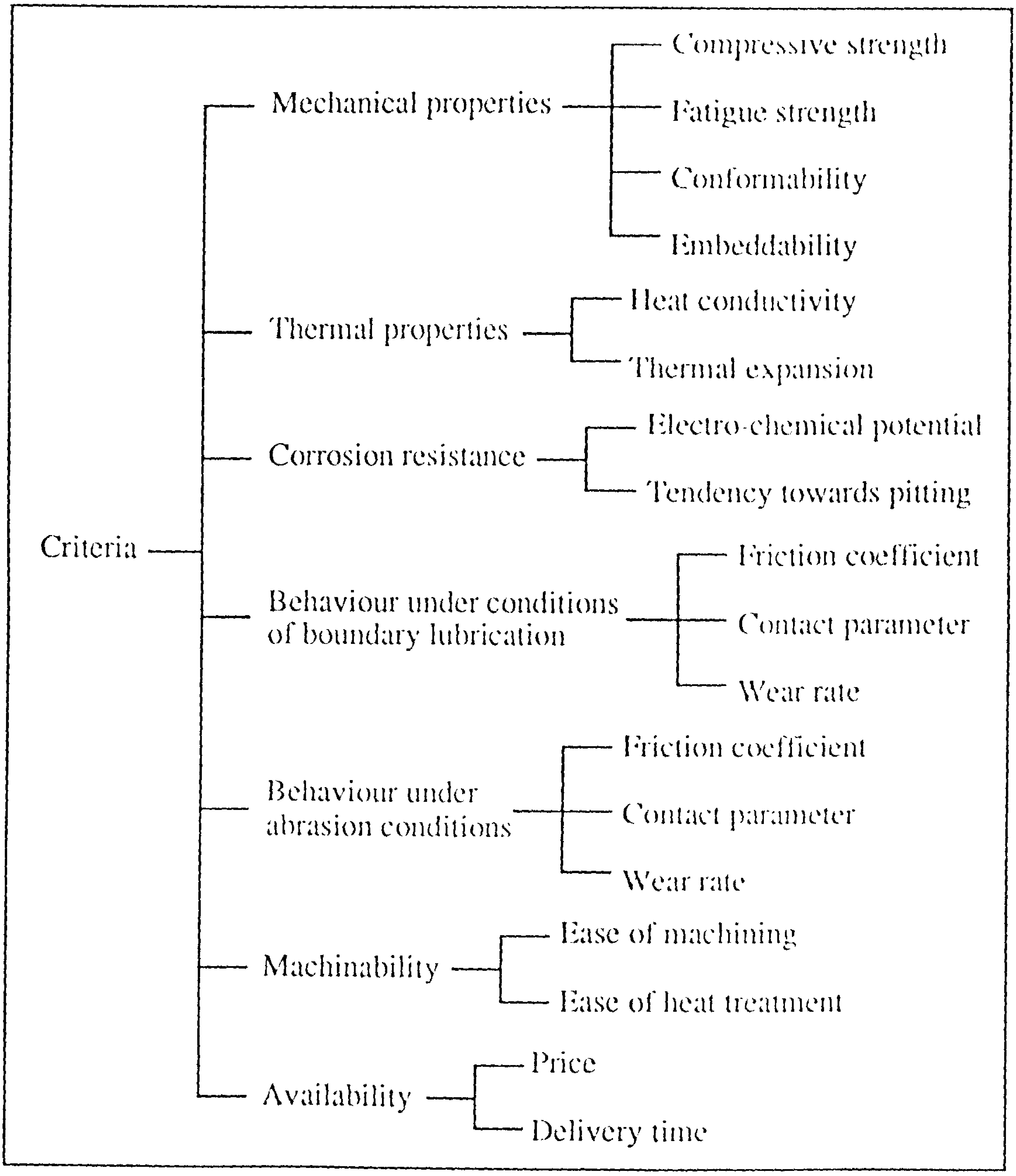


Figure 4.5 The criteria for the selection of bearing materials

4.3.4 Selection of design tolerances

The performance of bearings is substantually affected by errors from the design specification arising in the production process[18][71][72]. It is important that effective techniques are available for the production of each bearing component and the total bearing system.

There is a range of errors during production which have to be taken into consideration at the design stage. The range of errors include:

- Variations in bearing clearance.
- Variations in restrictor dimensions.
- Form errors.
- Local burring.
- Misalignment.

(1) Variations in bearing clearance: Figure 4.6 shows the basic relationship between the dimensions of the shaft, the bearing housing and the diametral clearance. Considering the extreme condition of manufacturing errors, the upper clearance limits $C_d(U)$ and the lower clearance limit $C_d(L)$ are given by

$$C_d(U) = D(U) - d(L) \quad (4.1)$$

$$C_d(L) = D(L) - d(U) \quad (4.2)$$

where D(U) and D(L) are respectively the upper and lower housing diameter limits, d(U) and d(L) are respectively the upper and lower shaft diameter limits.

The tolerance on the clearance:

$$T_{Cd} = C_d(U) - C_d(L) = [D(U) - D(L)] + [d(U) - d(L)]$$
$$= T_D + T_d$$

that is, the tolerance on the clearance T_{C_d} is equal to the sum of the tolerances on the shaft and the bearing housing.

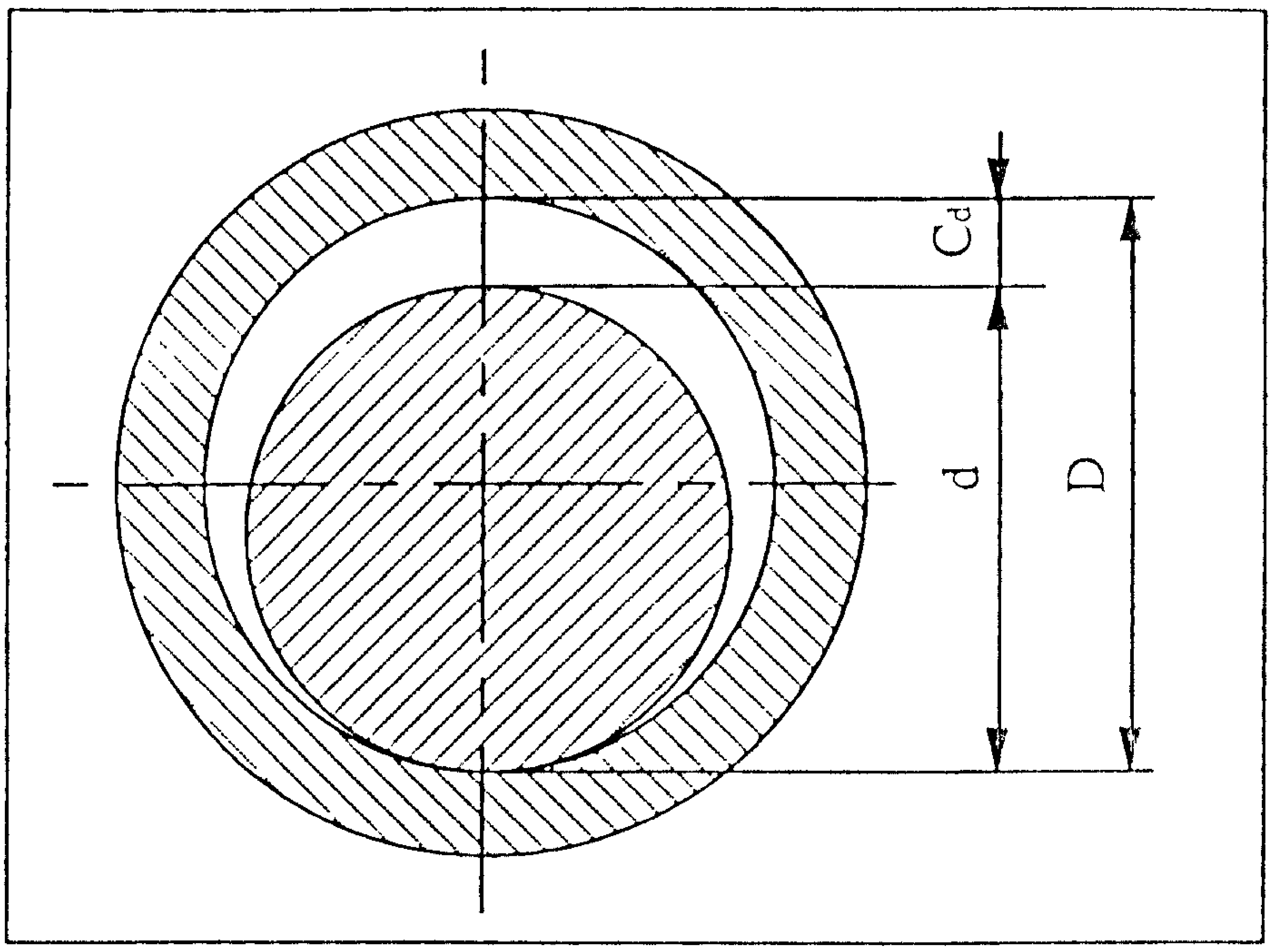


Figure 4.6 Relationship of the shaft, bearing housing and the diametral clearance

In a hydrostatic journal bearing in the concentric condition, the flow rate is[71]

$$q = \frac{p_s \beta B C_d^3}{8 \eta} \qquad (4.3)$$

and

$$\beta = \frac{1}{1 + \left(\frac{1 - \beta_o}{\beta_o}\right)\left(\frac{C_d}{C_{d_o}}\right)^3} \qquad (4.4)$$

The manufacturing tolerances on the shaft and bearing housing specify the permitted variations in diametral clearance and hence affect the range of flow rates q and pressure ratio β. The power of three for clearance variations in equation (4.3) and (4.4) shows that clearance strongly influences the bearing flow rate and further the bearing stiffness and load carrying capacity. Therefore, it is suggested to choose as small as possible tolerance values of shaft and housing such as IT5 generally for hydrostatic bearings and

IT4 for aerostatic bearings within manufacturing capability. It is possible to make an optimum combination of the tolerance grades of shaft and bearing housing based on the bearing performance and manufacturing capability.

(2) Variations in restrictor dimensions: Variations in restrictor dimensions directly affect bearing performance even though the effects may be greater or smaller for different restrictors. For instance, in a slot-entry hydrostatic bearing, the pressure ratio is[73]

$$\beta = \frac{1}{1 + \left(\frac{1-\beta_0}{\beta_0}\right)\left(\frac{C_d}{C_{d_0}}\right)^3\left(\frac{B}{B_0}\right)\left(\frac{y}{y_0}\right)\left(\frac{a_{s_0}}{a_s}\right)\left(\frac{z_0}{z}\right)^3} \qquad (4.5)$$

The thickness z of the shims is of the order of the bearing clearance. With a change of the shim thickness it is seen that the pressure may vary from the design pressure ratio

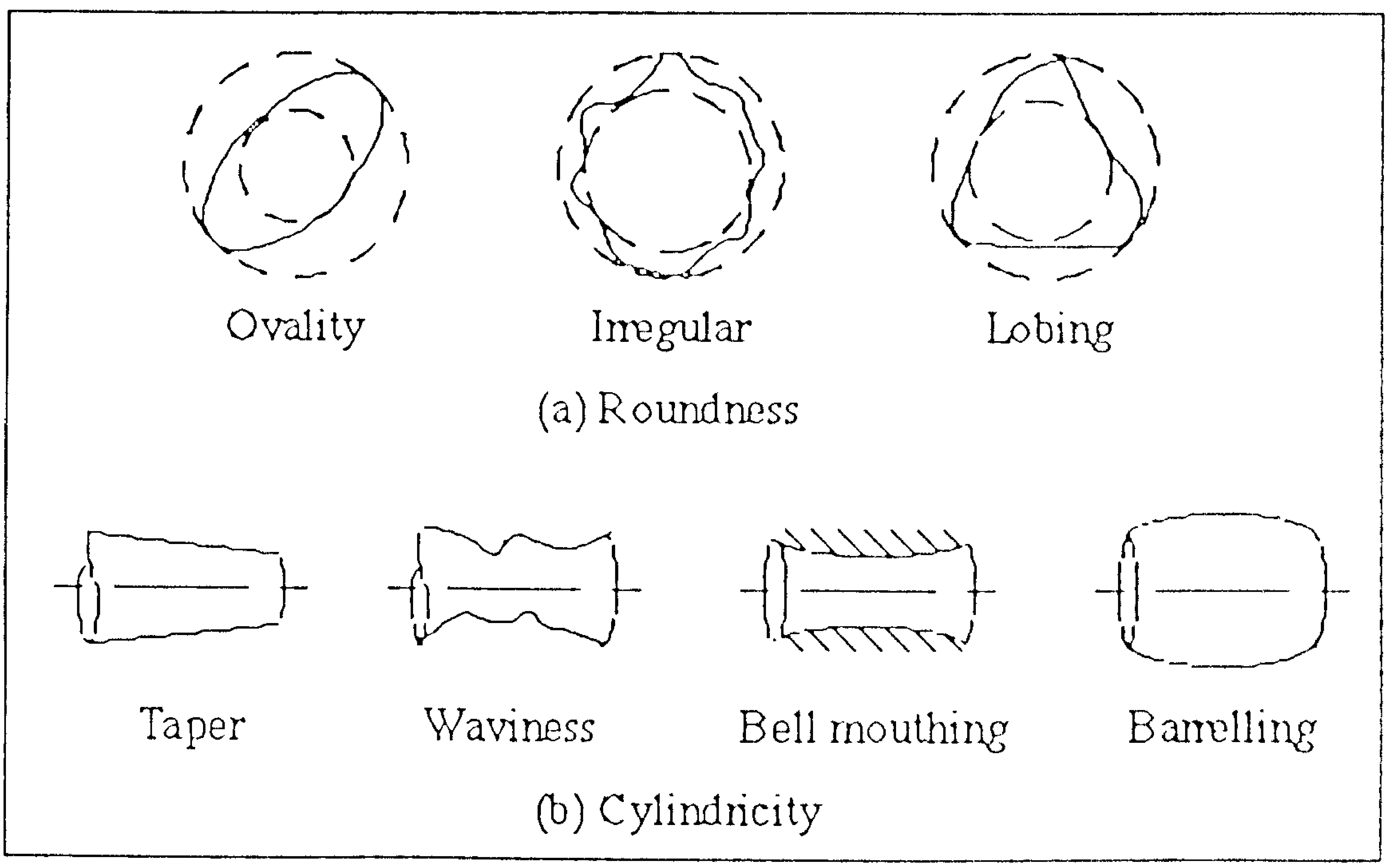


Figure 4.7 Typical form errors of the shaft and bearing housing

of 0.5 and hence there will be variations of bearing performance such as bearing stiffness and load carrying capacity. Therefore, the restrictor dimensions which directly affect the flow characteristics of a bearing have to be carefully considered during manufacture.

(3) Form errors: Typical form errors in roundness and cylindricity are shown in Figure 4.7. Although small in absolute size terms, these errors can be large when considered in relation to the design clearance. Therefore, the production of form errors of the shaft and the housing need to be paid careful attention during manufacture.

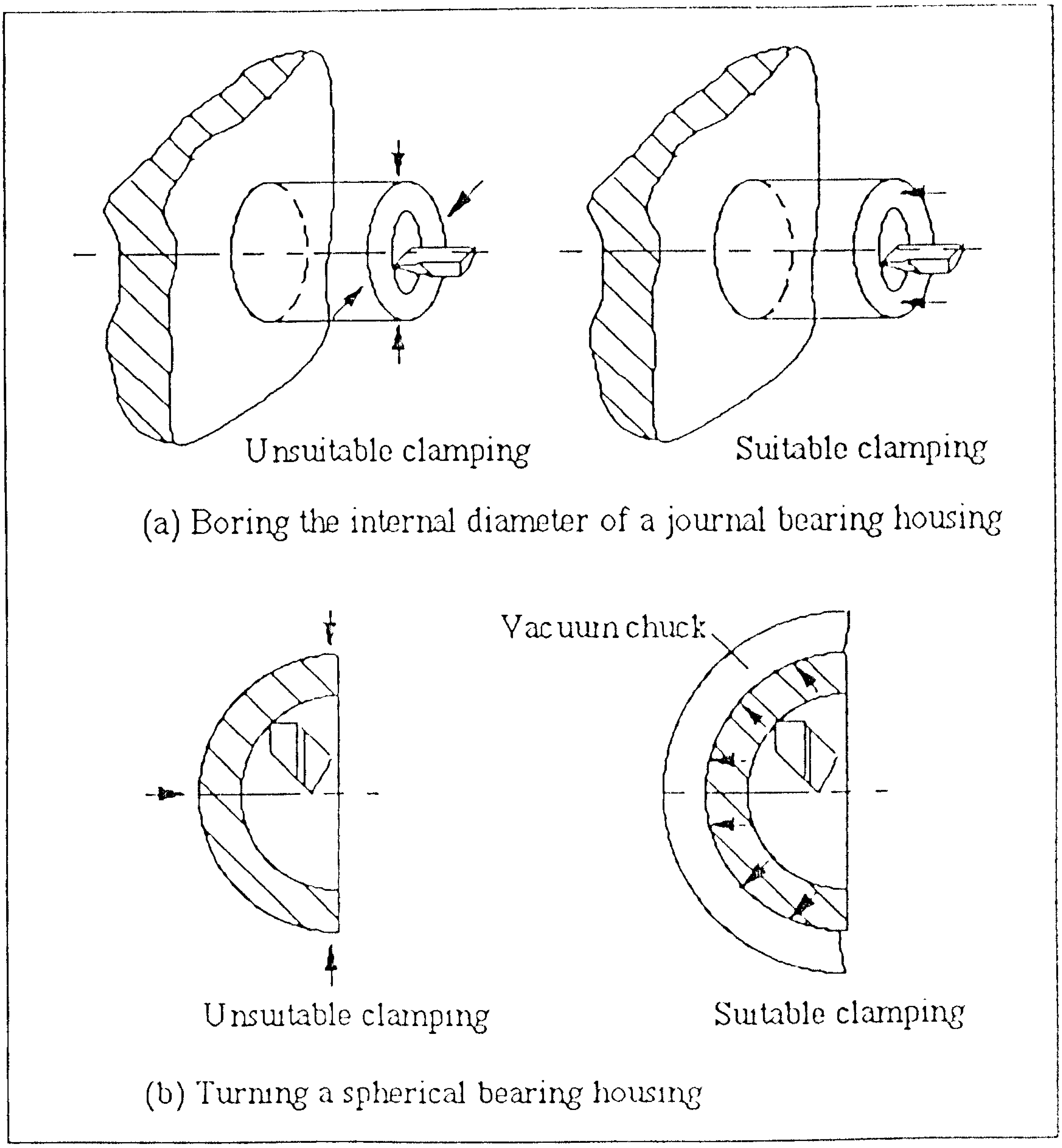


Figure 4.8 Correct clamping of the components during manufacture

Machine tools with high precision spindle rotation and slide straightness should be used to achieve the required bearing form accuracy. During manufacture, form errors may also result from clamping forces on the components, especially in the case of the bearing housing. Appropriate techniques should be employed to minimise this problem such as clamping on the insensitive direction of components or making the clamping force on the component evenly distributed as shown in Figure 4.8.

(4) Local burring: In the manufacture of aerostatic bearings with annular orifice or slot entry restrictors, burrs are usually formed at the edge of restrictors as shown in Figure 4.9. The burrs can be of the order of several micrometers. This phenomenon can have a large influence on load carrying capacity of the bearings because it affects local conditions at the entrance to the film. It is therefore necessary to employ deburring measures which will leave the edge undamaged.

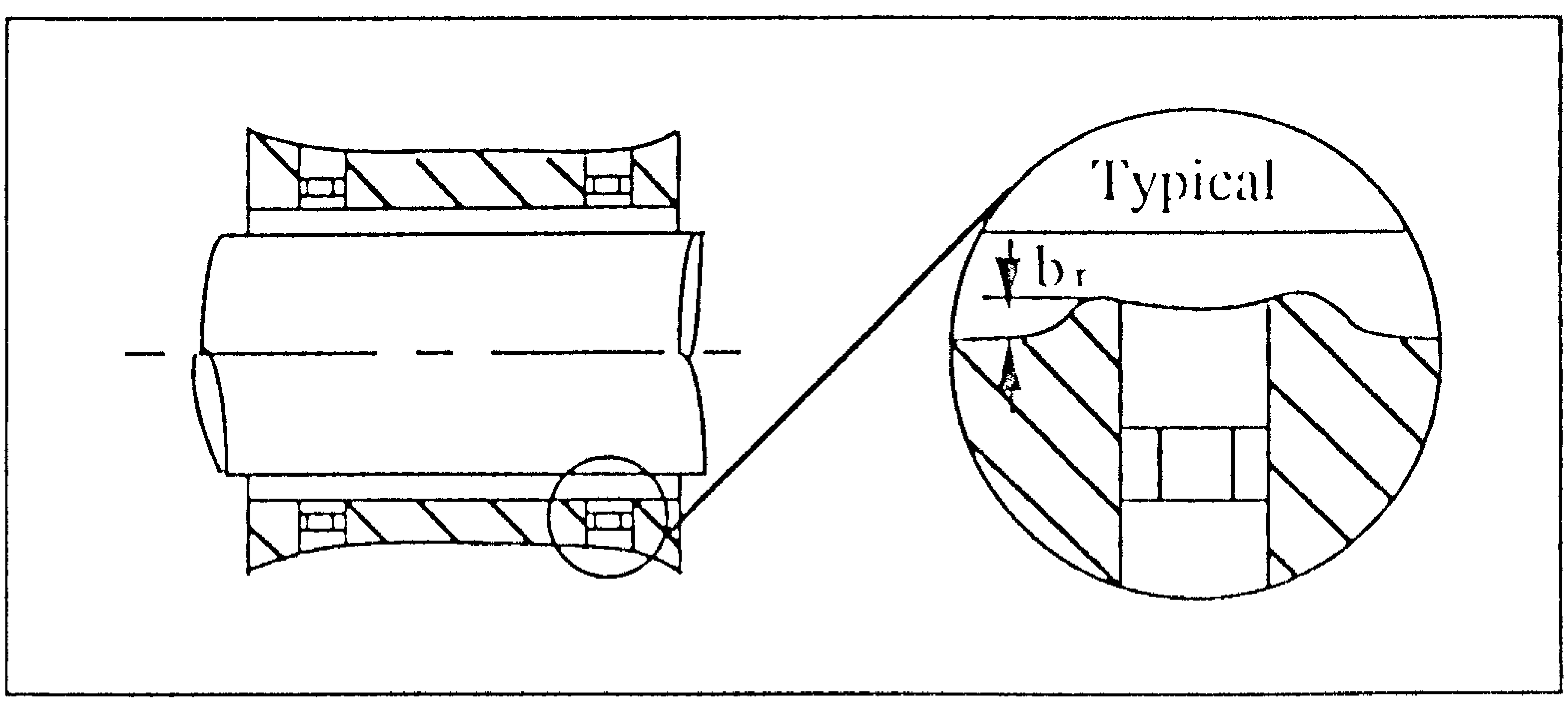


Figure 4.9 Burrs formed at the edge of restrictors

(5) Misalignment: Misalignment can occur in following ways:

- Due to elastic or thermal distortion of a bearing or shaft,
- Due to errors in aligning a bearing during machining and assembly,
- Due to bending of the shaft.

Misalignment reduces the bearing load carrying capacity by directly limiting the extent of eccentricity which can take place before touch down. To cope with these problems requires the selection of bearing housing and shaft structures with appropriate stiffness and achievement of aligning accuracy during manufacture.

4.4 Design theory for hydrostatic journal bearings

4.4.1 Reynolds equation

Reynolds equation is the governing equation for flow through the clearance of a fluid film bearing. The Reynolds equation may be expressed in a simplified form based on assumptions which include:

(a) that the lubricant is Newtonian, i.e. stress is proportional to rate of shear.
(b) the flow is laminar.
(c) fluid inertia may be neglected.
(d) the viscosity is constant through the film thickness.

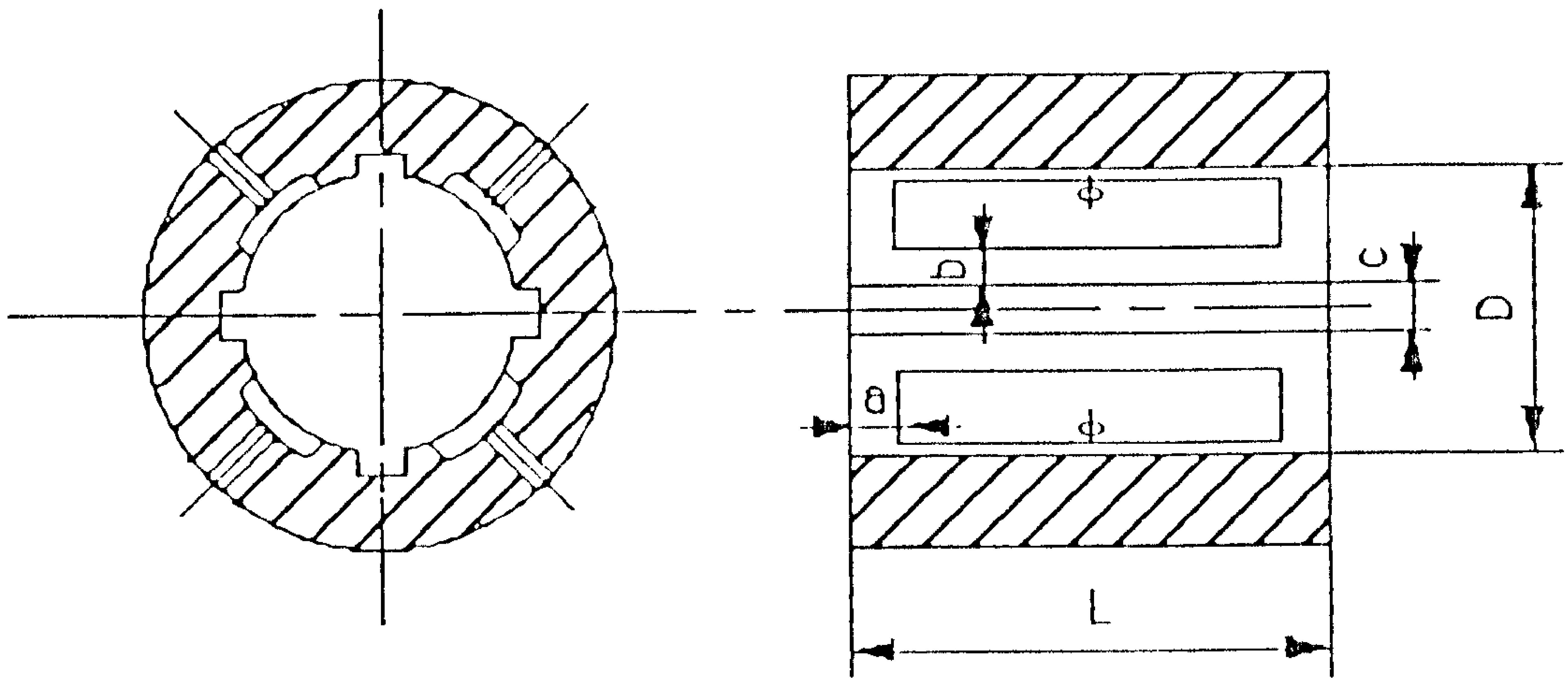
The simplified form of Reynolds equation can be written as[38]

$$\frac{\partial P}{\partial x}\left(h^3 \frac{\partial P}{\partial x} \right) + \frac{\partial P}{\partial y}\left(h^3 \frac{\partial P}{\partial y} \right) = 6U\eta \frac{dh}{dx} \qquad (4.6)$$

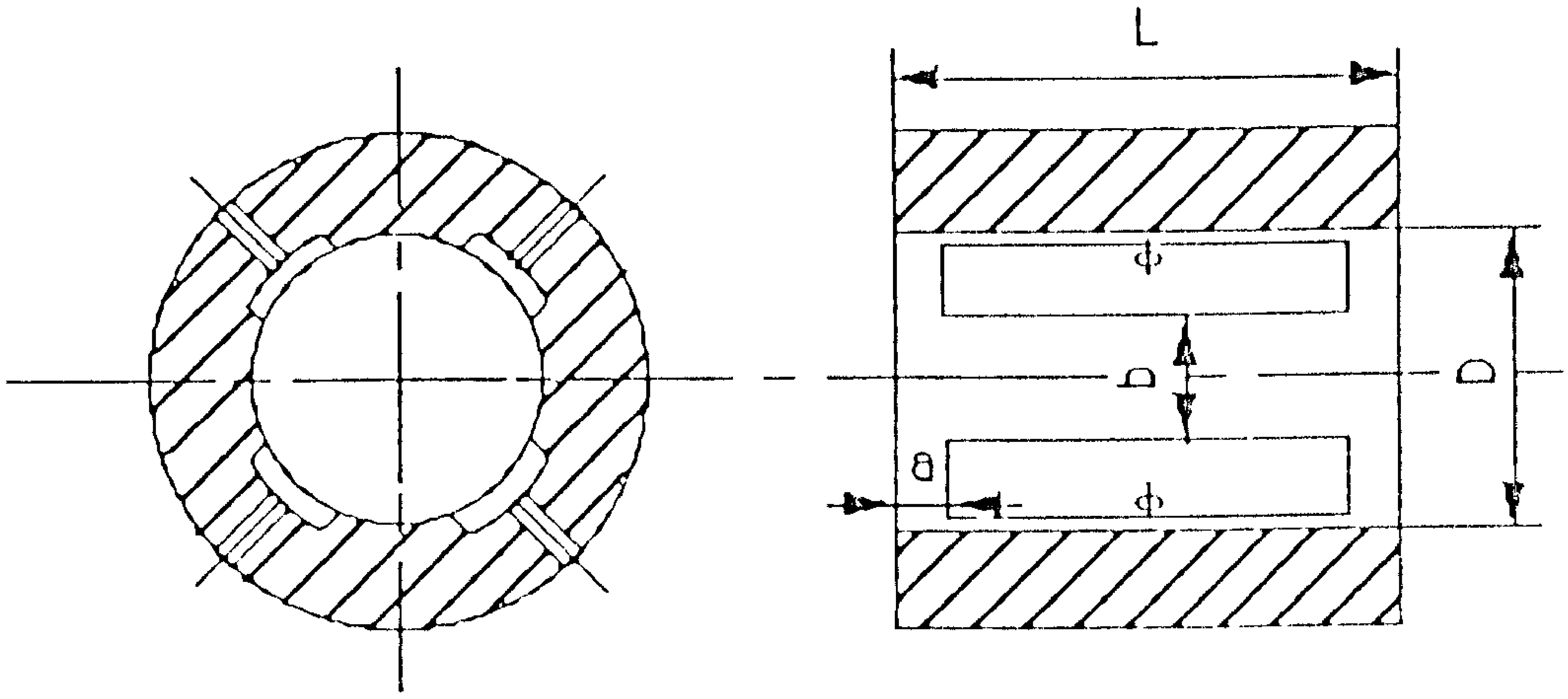
The equation expresses the relationship between the pressure gradients in the x (circumferential) and y (axial) directions and the surface velocity of the bearing. Reynolds equation can be solved by using numerical methods such as finite difference and finite element method and hence the bearing pressure obtained. Once the pressure distribution is known, the other properties of the film are readily determined.

4.4.2 A general design procedure

Although a designer needs to know the basis of the theory to fully understand the design procedures presented, it should not be necessary for the designer to calculate design data from first principles except in unusual cases. This is a major objective of developing a general design procedure which will minimise the number of calculations and eliminate as far as possible the need for complex theoretical manipulation. A designer can undertake design economically for a wide variety of bearing shapes and



a. The configuration with axial slots between recesses



b. The configuration without axial slots

Figure 4.10 Two typical configurations of hydrostatic journal bearing

sizes. When designing a hydrostatic journal bearing to operate at relative low speed, there are six design parameters which require detailed consideration. These are the bearing length to diameter ratio L/D, axial flow land width to length ratio a/L, and inter-recess land width to length ratio b/L as shown in Figure 4.10, bearing pressure ratio ß, bearing supply pressure P_s, and diametral clearance C_d. In addition other important parameters include the dimensions of the restrictors which may be capillary tube, slot or orifice. For a bearing which operates at speed further parameters require attention These parameters include lubricant viscosity η, the ratio of friction power H_f to pumping power H_p, and maximum rotational speed N at which the bearing operates. The correct design of the relevant parameters enables the bearing to achieve high load capacity, high stiffness and moderate flow-rate in addition to low total power dissipation.

The strategy employed in the design procedure is made up of several stages. It is described as follows[73]:

(a) Choose the bearing configuration and restrictor type, for example, recessed journal bearing with capillary restrictor.

(b) Determine the basic bearing parameters constrained by the machine design, for example:
load, W
diameter D and length L
shaft rotation speed, N

(c) Determine the basic bearing parameters which are if possible selected according to rules where these are available for optimal design or ease of manufacture, for example:
number of recesses, n
land width ratio, a/L
inter-recess land width ratio, b/L
length/diameter ratio, L/D
bearing radial clearance, h_o
concentric pressure ratio, ß
concentric power ratio, K
capillary length to diameter ratio l_c/d_c, if capillary restrictors are to be employed,
axial drain slot width c, if axial drain slots are to be used.

(d) Determine the basic bearing parameters which must be calculated, for example:

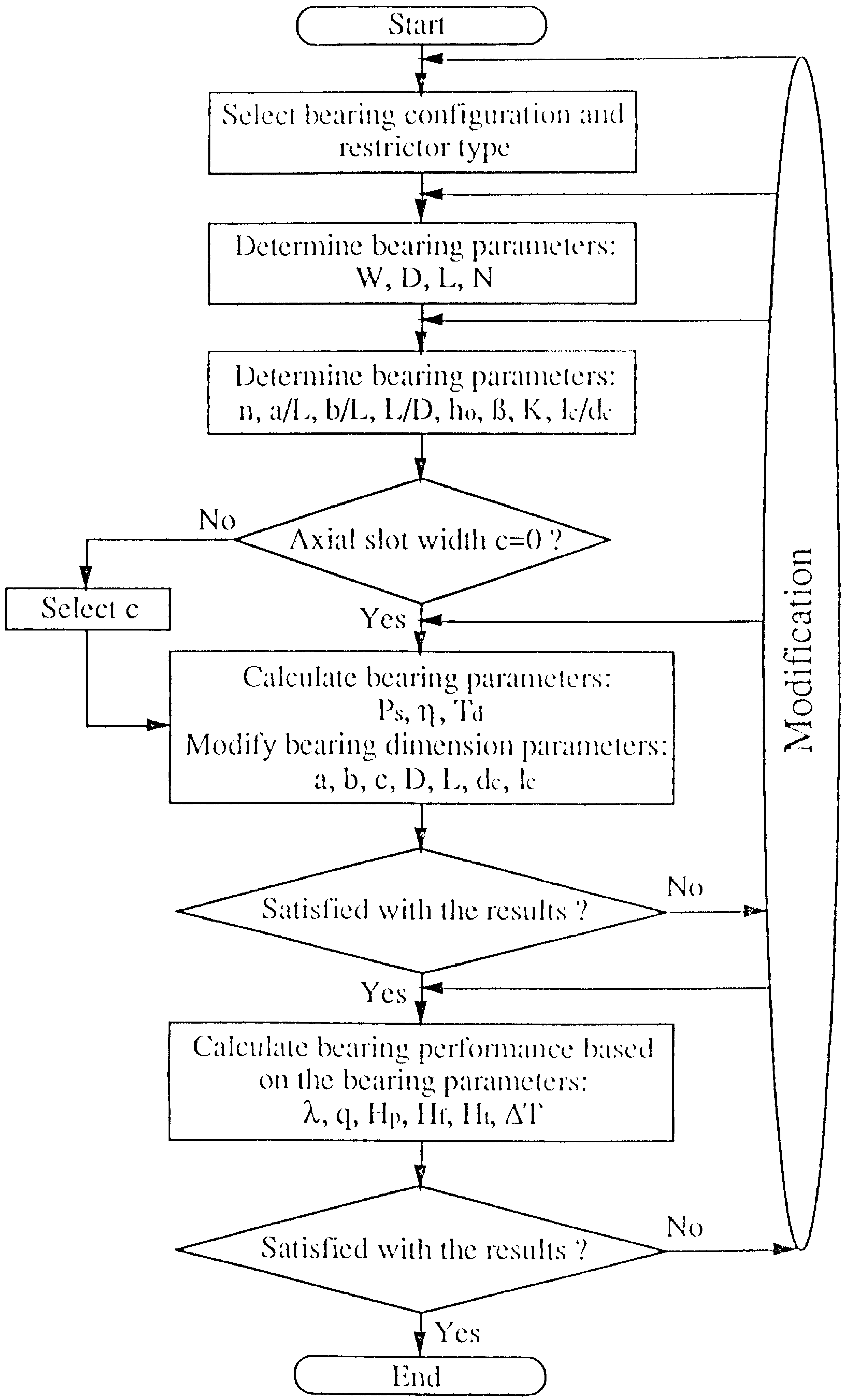


Figure 4.11 A flow chart of the design procedure for hydrostatic journal bearings

supply pressure P_s, from $P_s = \frac{W}{D^2 W}$, where W is provided as computed data.

viscosity η, $\eta = S_h \left(\frac{P_s}{N}\right)\left(\frac{C_d}{D}\right)^2$

clearance tolerance, T_{Cd}

(e) Calculate the bearing performance data, for example:

stiffness, λ

flow rate, q

pumping power, H_p

friction power, H_f

total power, H_t

maximum temperature rise, ΔT

(f) Design the restrictor for appropriate flow rate and pressure ratio, for example, determine the capillary dimensions, d_c and l_c.

Figure 4.11, illustrates the design strategy in the form of a flow chart. For different bearing configurations such as conical and spherical ones, the bearing geometry parameters can be different. However, the design strategy and procedure can be suitable for all hydrostatic journal bearings in spite of their specific configurations.

4.4.3 Optimisation

One major difficulty involved in the design of hydrostatic bearings is the need to select a great number of parameters, so that the bearing designed can have the optimum performance for the specified service conditions. In many design cases minimising the power consumption for maximum load support is the first objective taking into consideration the power unit cost. The designer can easily vary from this criterion to achieve other objectives such as low temperature rise because high power dissipation tends to result in high temperature rise, large oil viscosity variation and large thermal distortion in the machine structure[38].

In a hydrostatic journal bearing, the total power is the sum of the pumping power and the friction power under concentric operating conditions:

$$H_t = H_p + H_f \tag{4.7}$$

Pumping power H_p is the rate at which energy must be expended to force the liquid through the bearing. Friction power H_f is the rate at which energy must be expended to move the bearing. Expressions for these are as follows:

$$H_p = P_s . q = \frac{P_s^2 \beta B h^3}{\eta} \tag{4.8}$$

$$H_f = F . U = \frac{\eta A_f U^2}{h} \tag{4.9}$$

From equations (4.8) and (4.9)

$$H_t = H_p + H_f = \frac{P_s^2 \beta \bar{B} h^3}{\eta} + \frac{\eta A_f U^2}{h} \tag{4.10}$$

The optimisation of the bearing parameters can be achieved by taking equation (4.10) as the objective function subject to constraints. There are two approaches to carrying out the optimisation:

(i) The total power H_t is minimised for a specific design variable by partially differentiating Equation (4.10) with respect to the variable and setting the result to zero. Optimum values of the design parameter variables are then determined by using analytical methods to ensure one of major bearing physical constraints is satisfied. This approach is based on the inherent physical concepts of the bearing and ease of use.

(ii) The total power H_t is minimised under some constraint conditions which may be one or more of the following:

Power ratio $K_{min} \leq K \leq K_{max}$

Pressure ratio $\beta_{min} \leq \beta \leq \beta_{max}$

Radial clearance $h_{o\,min} \leq h_o \leq h_{o\,max}$

Stiffness $\lambda \geq \lambda_{min}$

Flow rate $q \leq q_{max}$

Temperature rise $\Delta T \leq \Delta T_{max}$

Optimum values of the design variables are determined by using an iterative numerical method. The second approach is based on numerical computer optimisation rather than mathematical solutions and deductions based on physical concepts. The second approach is capable of high accuracy where the constraints are selected with values consistent with optimal performance but requires greater computing effort

4.4.3.1 Approach one - mathematical optimisation

(a) Optimum viscosity

The designer may minimise the total power by choosing the optimum value of viscosity. The process of finding the optimum viscosity is to vary the value of viscosity with all other design parameters fixed at the constant value appropriate for the design requirements, that is

$$\frac{\partial H_t}{\partial \eta} = -\frac{P_s^2 \beta \bar{B} h^3}{\eta^2} + \frac{A_f U^2}{h} = \frac{H_f}{\eta} - \frac{H_p}{\eta}$$

so that $\frac{\partial H_t}{\partial \eta} = 0$ when

$$H_p = H_f$$

The corresponding power ratio is $K = H_f/H_p = 1$.

(b) Optimum clearance

As explained when considering the optimum viscosity, the optimum clearance can be found by partial differentiation when

$$\frac{\partial H_t}{\partial h} = \frac{3P_s^2 \beta \bar{B} h^2}{\eta} - \frac{\eta A_f U^2}{h^2} = \frac{3H_p}{h} - \frac{H_f}{h}$$

so that $\frac{\partial H_t}{\partial h} = 0$ when

$$3H_p = H_f$$

The corresponding power ratio is $K = H_f/H_p = 3$.

(c) Optimum power ratio

From an extension of the foregoing techniques, it may be shown that the optimum value of power ratio for a recessed hydrostatic journal bearing with a certain working speed always lies in the range $1 \leq K \leq 3$. It has been demonstrated that whichever route is used for optimisation, the total power only varies by approximately 15%[74]. This is not a large variation when considered in terms of the need for a manufacturing tolerance. As long as the power ratio K is in the range $1 \leq K \leq 3$, the minimum power will not be exceeded by more than this value of 15%.

(d) Optimum land width ratio

The ratio of total power to applied load is

$$\frac{H_t}{W} = \frac{(1+K)H_p}{W} = (1+K)\frac{\left(\frac{W}{A\bar{A}}\right)^2 \beta B h^3}{W\eta} = (1+K)\frac{\beta W}{A^2}\frac{h^3}{\eta}\frac{B}{\bar{A}^2}$$

This may be written

$$\frac{H_t}{W} = (1+K)\frac{\beta W}{A^2}\frac{h^3}{\eta}\overline{H_p}$$

The maximum load for the minimum power is achieved for the bearing shape which makes $\overline{H_p}$ a minimum. For a recessed hydrostatic journal bearing

Total projected area $A = LD$

Effective area $A_e = A\bar{A}$ is proportional to $D(L-a)$

Hence $\bar{A}$ is proportional to $\frac{L-a}{L}$

Flow shape factor $\bar{B} = \frac{C}{6an}$ $\quad C = \begin{cases} (\pi D - nc - nb)(1 + r) & \text{with axial slots} \\ \pi D & \text{without axial slots} \end{cases}$

so that

$$\bar{H}_p = \frac{\bar{B}}{\bar{A}^2} \text{ and is proportional to } \frac{C}{6an} \frac{L^2}{(L-a)^2}$$

An optimum for $\bar{H}_p$ may be determined by partial differentiation of H_p with respect to 'a' and equating to zero. It is found that the optimal value of a is L/3. At increasing eccentricity the optimum value of land width a shifts to L/4[38].

4.4.3.2 Approach two - numerical optimisation

There are tens of parameters for a hydrostatic journal bearing. If the value of one is changed the values of other parameters must be adjusted to restore an optimal condition. Ideally, total power consumption should be used as the objective function. A search is required to achieve the optimal values of bearing parameters which best satisfy the imposed constraint conditions.

In the general design procedure, the value of supply pressure P_s is of primary importance, since it must be sufficient to support the load. Other parameter values depend on their relationship with supply pressure. Therefore, the design search for the optimum value of supply pressure P_s is taken as the starting point for the achievement of minimum total power. The minimisation search can accommodate the following constraint conditions:

Power ratio $K_{min} \le K \le K_{max}$

Pressure ratio $\beta_{min} \le \beta \le \beta_{max}$

Radial clearance $h_{o\,min} \le h_o \le h_{o\,max}$

Stiffness $\lambda \ge \lambda_{min}$

Flow rate $q \le q_{max}$

Temperature rise $\Delta T \le \Delta T_{max}$

Clearly, some of the constraint conditions can be defined based on the results from Approach one, so that the optimisation searches are more efficient and reliable.

For a single variable search, there are three common search methods. These are the bisection search, the Fibonacci search and the golden section search. Compared with the other two methods, the golden section search has the advantages of simplicity and efficiency[75]. Figure 4.12 illustrates the algorithm developed to search for the optimum value range of the supply pressure P_S. The algorithm is operated in accordance with the minimisation of total power H_t. When the required accuracy of minimisation of H_t is achieved under the defined constraint conditions, the iterative search for the optimum value of P_S stops. All other design variables are eventually determined to correspond with this optimum value of P_S.

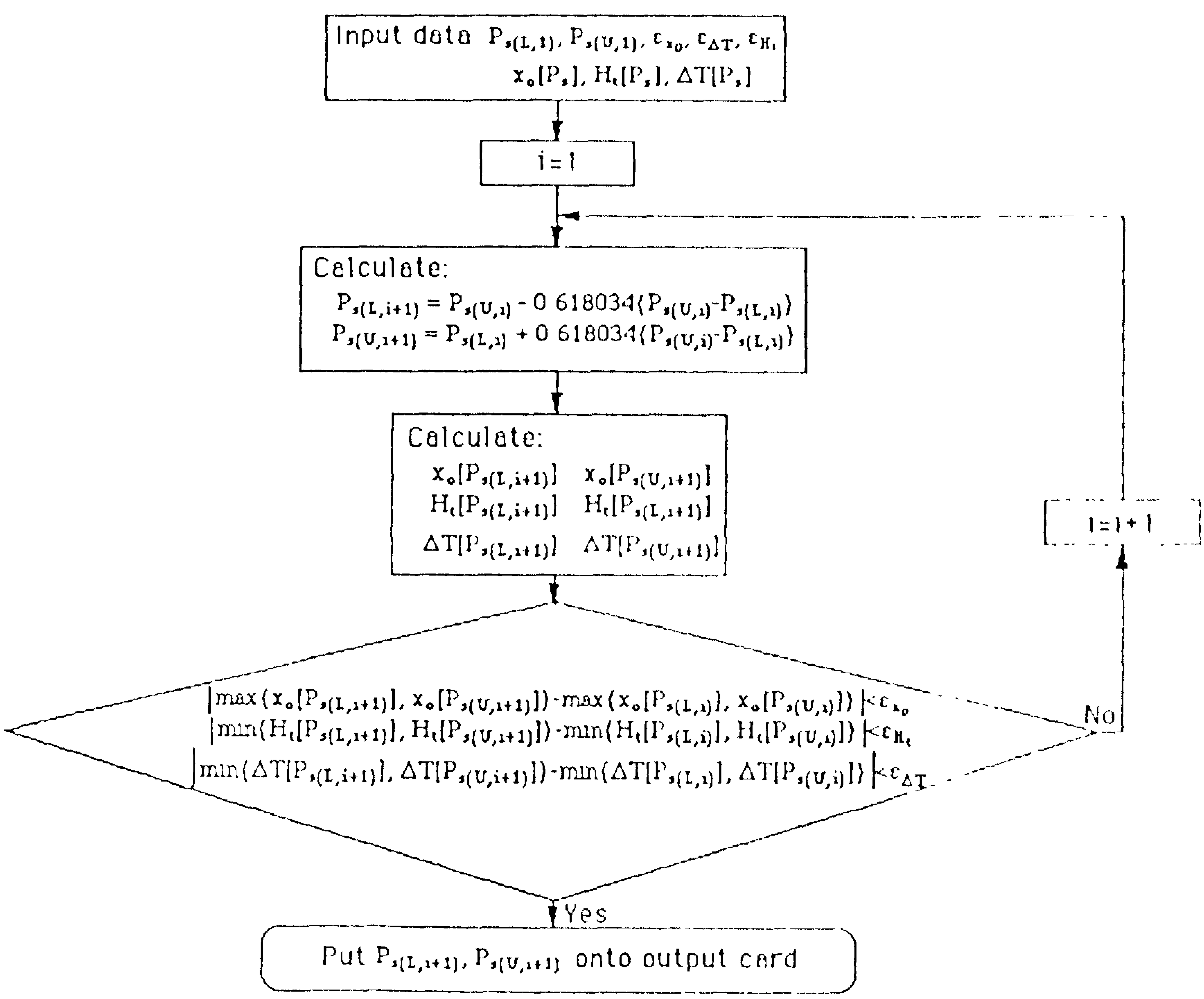


Figure 4.12 The algorithm employed to search for optimum supply pressure P_S

4.5 Design theory for aerostatic journal bearings

4.5.1 Design parameters

The governing equation of a gas film differs from that of a liquid film by the appearance of the density ρ of gas[76]. The steady compressible version of the Reynolds equation for an isoviscous gas can be written

$$\frac{\partial P}{\partial x}\left(\rho.h^3\frac{\partial P}{\partial x} \right) + \frac{\partial P}{\partial y}\left(\rho.h^3\frac{\partial P}{\partial y} \right) = 6U\eta\frac{\partial(\rho.h)}{\partial x} \qquad (4.11)$$

Since the energy dissipated by frictional forces is very small in normal aerostatic bearing operation, it is assumed that the temperature of the gas film remains constant and $P = k\,\rho$ where k is a physical coefficient; Equation (4.11) becomes

$$\frac{\partial P}{\partial x}\left(h^3\frac{\partial P^2}{\partial x} \right) + \frac{\partial P}{\partial y}\left(h^3\frac{\partial P^2}{\partial y} \right) = 6U\eta\frac{\partial(\rho.h)}{\partial x} \qquad (4.12)$$

The solution of the Reynolds equation determines the pressure distribution throughout the gas film between the bearing surfaces. After the pressure distribution has been determined, the other properties of the bearing may be readily determined.

Figure 4.13, shows the configuration and specification of the geometry of a typical aerostatic journal bearing. There are five parameters which require detailed consideration when designing a bearing[31]:

- Bearing length to diameter ratio L/D.
- Axial land width to length ratio a/L.
- Bearing gauge pressure ratio $K_{go} = \frac{P_d - P_a}{P_o - P_a}$
- Bearing gauge supply pressure $(P_o - P_a)$.
- Diametral clearance $C_d = 2h_o$.

There are other important parameters which include the dimensions of the inlet source required to achieve the required pressure ratio and flow rate, and the number of inlet sources around the bearing. All of the above parameters are interrelated. The basic relationships are defined as follows:

Load capacity $W = (P_o - P_a)\, LD\bar{W}$

Stiffness $\lambda = \dfrac{(P_o - P_a)\, LD\bar{\lambda}}{h_o}$

Flow rate $q = \dfrac{(P_o^2 - P_a^2)\, h_o^3\bar{q}}{h_o}$

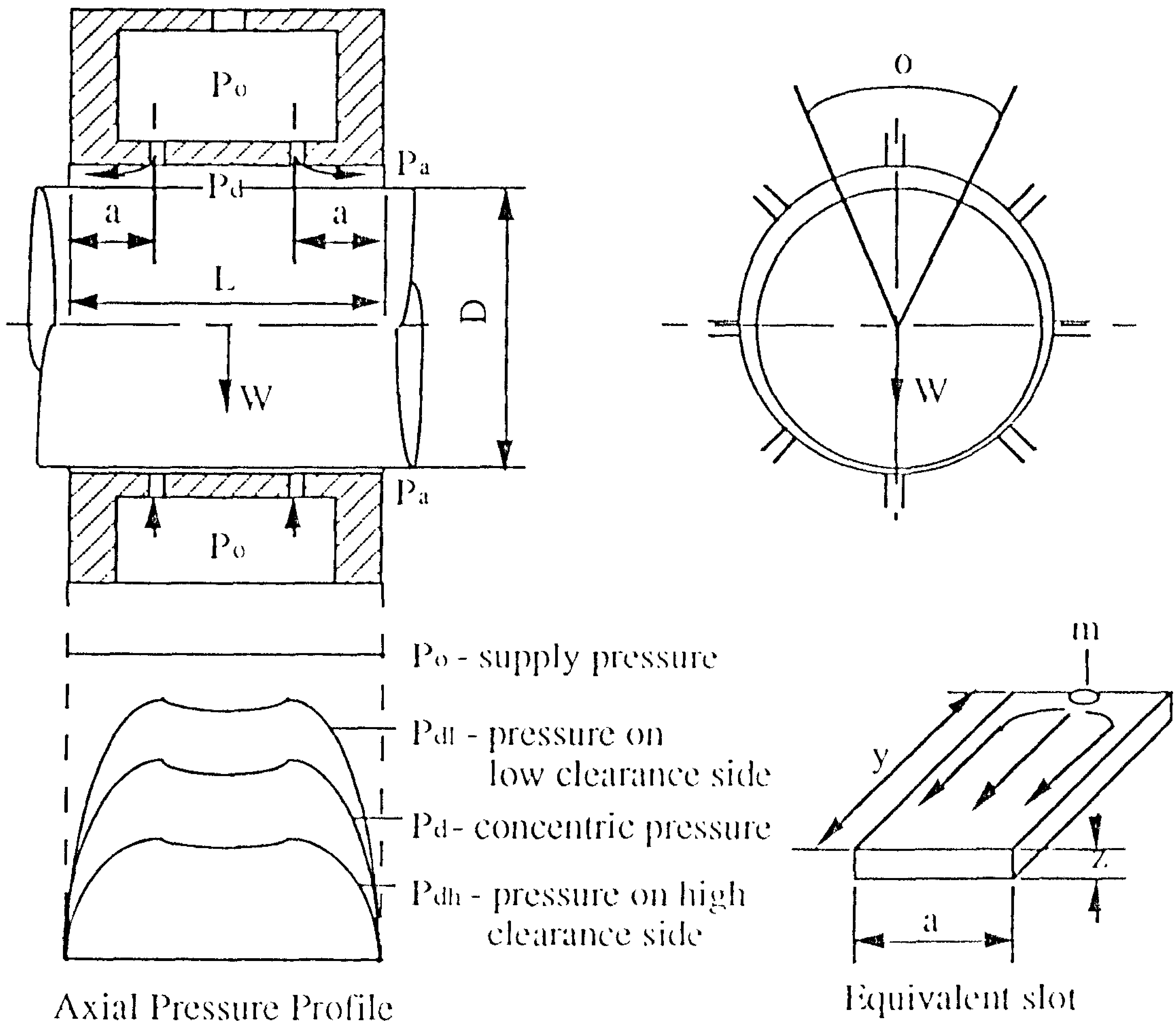


Figure 4.13 Description of the bearing geometry

4.5.2 Design criteria

The following design criteria are critical for the achievement of an optimum bearing design:

(a) The load parameter of a bearing is reduced as the value of L/D increases. However, increasing the bearing dimension L for a constant value of D increases the load the bearing will carry due to the increase in bearing area. The net result with increasing length is a law of diminishing returns. The recommended value of L/D is 1.0 which should be used where possible.

(b) Axial land width to bearing length ratio a/L defines the position of the inlets source. At the normal operating eccentricity ratio $\varepsilon = 0.5$ it is seen that reducing a/L towards 0.1 marginally increases the load parameter. This advantage is offset by the reduced ultimate load capacity, the large increase in flow rate and hence the air consumption. A good compromise which gives high load capacity without incurring excessive flow rate is a/L = 0.25[31].

(c) An acceptable range of pressure ratio K_{go} which leads to a high load parameter is $0.25 < K_{go} < 0.65$.

(d) A typical range of supply pressure achievable from a commercial air compressor is $0.3 \sim 0.8$ MN/m^2.

(e) The bearing clearance affects both flow rate and stiffness. It is good design practice to select the smallest value of clearance consistent with manufacturing constraints. As an appropriate guide to clearance, the bearings are usually manufactured to an air film thickness in the range of $2h_o/D = 0.0005 \sim 0.0015$.

(f) It is preferable to use pocketed orifices as these lead to greater stiffness. However, when pocketed orifices are used the designer must give consideration to the avoidance of pneumatic hammer instability. To prevent this instability the pocket volume must be kept to a minimum. The design criteria are:

- The total volume enclosed in the pockets is less than one twentieth of the film volume.
- The curtain flow area $\pi d_r h$ is at least twice the pocketed orifice flow area $\pi d_o^2/4$. This ensures that predominantly pocketed compensation is achieved.

4.5.3 A general design procedure

The design procedure is as follows:

(a) Clarify the basic bearing parameters constrained by the machine design, for example:

load, W

external dimensions, diameter D and length L

shaft rotation speed, N

stiffness, λ

(b) Choose the bearing configuration and type of restrictor, for example, single or double row entry, pocketed or annular orifices.

(c) Determine the basic bearing parameters which are if possible selected according to established design criteria where these are available. The design criteria may relate to optimum design or ease of manufacture. Values to be established are:

number of orifices per row, n

land width ratio a/L for a double row entry bearing

length/diameter ratio, L/D

radial bearing clearance, h_o

concentric pressure ratio, $K_{go} = (P_d-P_a)/(P_o-P_a)$

(d) Calculate the bearing performance data, for example:

stiffness, λ

load carrying capacity, W

flow rate, q

(e) Calculate the air inlet restrictor dimensions to ensure that the restrictor exhibits the characteristics required, for example, orifice diameter d_o and pocket depth h_p with which pneumatic hammer instability can be avoided.

Figure 4.14 illustrates the design procedure in the form of a flow chart.

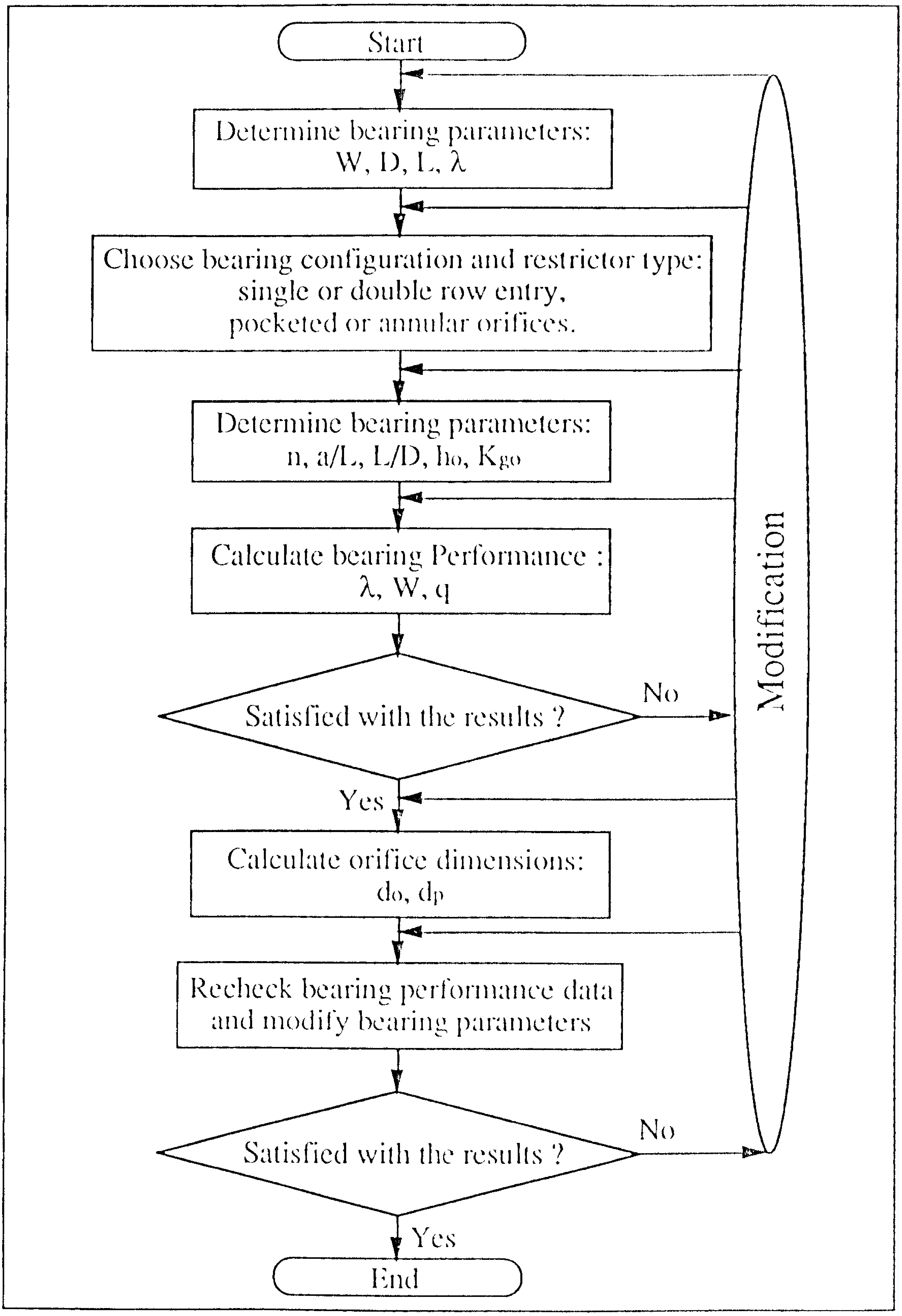


Figure 4.14 A flow chart of the design procedure

4.6 A general design procedure for externally pressurised journal bearings and its computerised solution

Based on the design procedures for hydrostatic and aerostatic journal bearings, a general design procedure is formulated for externally pressurised journal bearings. The general procedure applies for both hydrostatic and aerostatic bearings. The basic procedure is as follows:

(a) Determine the basic bearing parameters constrained by the machine design, for example, the bearing load, shaft rotation speed, and external dimensions.
(b) Decide the bearing type employed, e.g. a hydrostatic bearing or an aerostatic bearing.
(c) Choose the bearing configuration, restrictor type and materials.
(d) Determine the basic bearing parameters which are if possible selected according to established design criteria where these are available for optimum design or ease of manufacture.
(e) Determine design parameters including the bearing geometry and lubricant and supply system properties.
(f) Calculate the bearing performance.
(g) Calculate the restrictor dimensions to ensure that the restrictor exhibits appropriate characteristics.

The procedure is not a linear consequence of design activities. At any design stage, information associated from other stages may be involved. At each stage, refinement and modification occur based on feedback involved at that stage or from other stages. A designer considers a variety of design requirements within the decision-making process. The decisions may include selection, computation, analytical derivation and synthesis. An optimum design is the outcome of a compromise between various design requirements.

A conventional design aid with only computational support cannot easily fulfil the demands of the bearings design procedure. An interactive intelligent design support system is needed to implement the procedure. Figure 4.15, shows a schematic diagram of an envisaged design support system for externally pressurised journal bearings. The

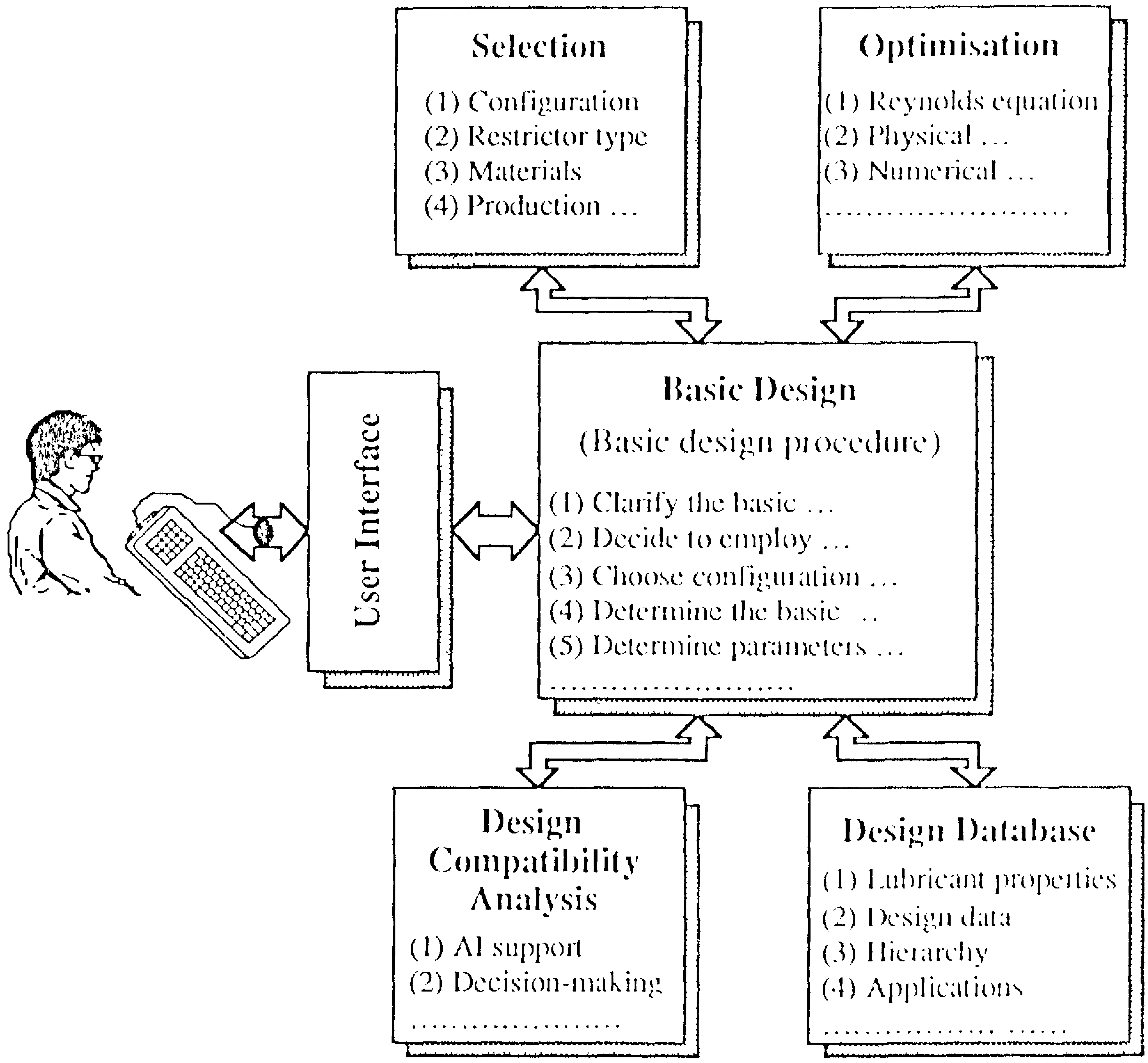


Figure 4.15 A block diagram of a bearing design support system

system has five functional modules. The basic design module incorporates the design procedure described above and is the kernel of the system. The other four modules are the selection, optimisation, design compatibility analysis (DCA) and design database modules. These four modules are essential and operate with the design module to achieve a bearing design. The selection module undertakes the selection of the bearing type, configuration, restrictor, material and production techniques. The DCA module identifies any incompatibility between the design requirements and the design solution, explains the flaw, and suggests modifications to improve the design. Both the selection and DCA modules incorporate inferential intelligence drawn from design expertise. The optimisation module searches for an optimum value of a parameter based on physical and numerical optimisation methods. The design database includes a variety of design data in the form of text, graphics, engineering drawing, digital numbers, programs, and images. The design database is developed using hypermedia technology. The user interface and the interface between modules are also designed using hypermedia technology

The computerised solution emphases the integration of AI, hypermedia and optimisation techniques together with the conventional design techniques. Hypermedia, in particular, provides a new approach to the representation of engineering knowledge and engineering data[77]. The integration makes it readily possible for the designer to retrieve design information, use the embedded bearing expertise efficiently, and achieve an optimal bearing design taking into account numerical and qualitative issues. The integration also makes it possible to develop a higher level design aid usable by the broad engineering community.

Part II Development of the System

Chapter 5 System configuration

5.1 Introduction

In Chapter 4, an approach to computerised bearing design was proposed. A schematic arrangement of the bearing design support system was proposed. This chapter deals with the problems of configuring the system. The system is required to provide a powerful design assistance covering the full design process. The support should be effective, efficient, user-friendly and inexpensive.

5.2 Selection of a system development tool

The selection of a system development tool or environment is an early but critical step in the system development process. Experienced developers of software systems justifiably argue that they have to work doubly hard when a tool does not well suit the system problem[61].

Presently there are tens of microcomputer-based intelligent system development tools that include both hypermedia and AI capacities. These tools vary significantly in their approaches to knowledge representation, inferencing strategies, the way they integrate or implement hypermedia, and in their price and ease of development. Based on the criteria discussed in section 3.3, Apple Corporation's HyperCard was selected for the development of the design support system.

Since its introduction, HyperCard has become the most widely used hypermedia authoring tool. This is in part attributable to Apple Corporation's free distribution of HyperCard with Macintosh computers since 1987 and promotion of the product as the next wave in end-user computing. The key to HyperCard's authoring environment is HyperTalk, a programming language built into HyperCard. HyperTalk has features such as looping structure, variables, if-then statement, symbolic manipulation, and input/output ability. It is more a traditional program language than a hypermedia authoring language, although it has a syntax that is easy to use. Programs written in

HyperTalk can cope with quite complicated numerical computations and also with logic operations which are essential for AI based programming[78]. A conceptual structure of the HyperCard environment is illustrated in Figure 5.1, with HyperTalk scripts being linked to various HyperCard objects such as buttons, fields, cards, backgrounds, and stacks.

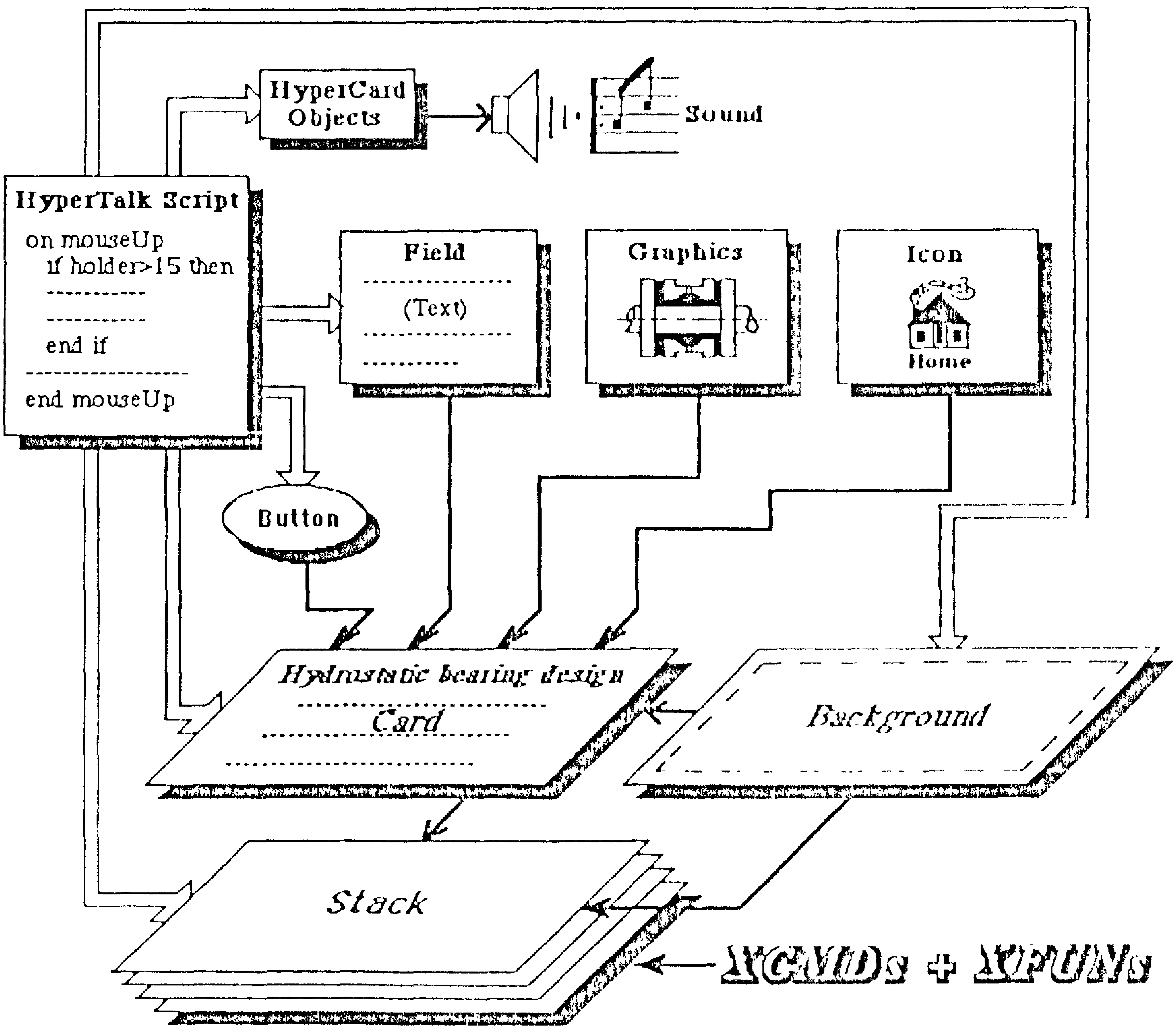


Figure 5.1 The conceptual structure of the HyperCard environments

Other features which are quite useful in constructing a powerful design support system with HyperCard are its painting tools, its ability to alternatively hide and display information, and its Macintosh user-friendly 'WIMP' interface. 'WIMP' is derived from Windows, Icons, Menus and Pointing, and at the time of its introduction represented a radical step forward in designing user-friendly software systems[79].

5.3 System structure design

A conceptual framework for the design support system was described in section 4.6. The schematic layout arises mainly from the requirements of the bearing design approach. In the system development, both functional and operational issues of the system will be considered with particular reference to the application of the HyperCard environment. For example, the issues include the implementation of the design approach, system construction, and human-computer interactions.

5.3.1 System framework

As illustrated on the system 'Home' card in Figure 5.2, the developed system consists

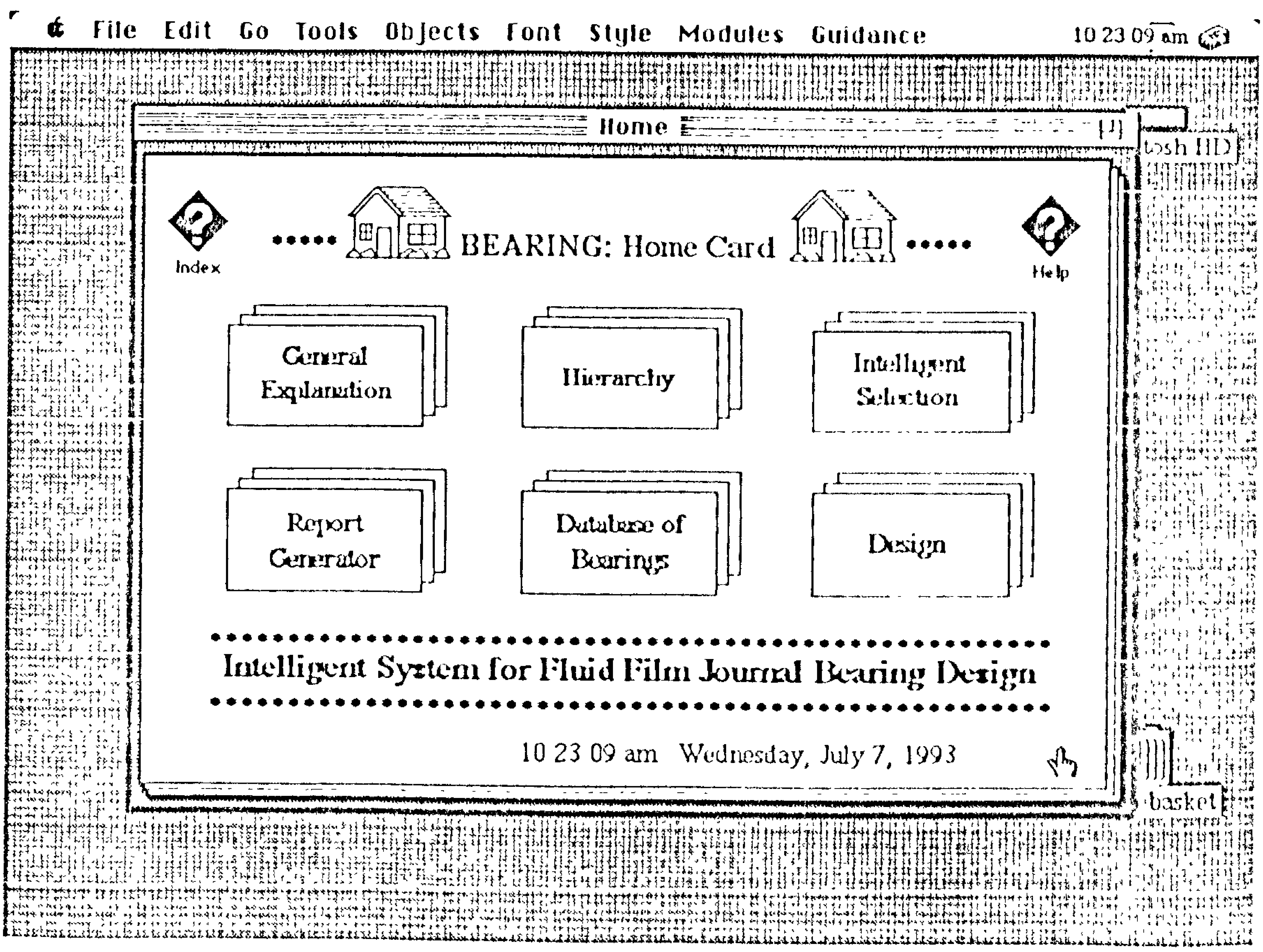


Figure 5.2 The system 'Home' card

of six main functional modules and two auxiliary modules The functional modules are a general explanation module, a hierarchy module, an intelligent selection module, a design module, a bearings database module, and a report generator module. With the functional modules, a system user can retrieve the bearing multimedia style knowledge within the system, undertake selection and design the bearing configuration and the control device. Finally the design results may be printed as a report. The user can also access the index auxiliary module to help him search the information inside the system and to get the help module for the users on-line help.

Figure 5.3 illustrates the diagram of the system basic framework[80]. The 'Home' card acts as a master menu card for the system. All of the modules are connected to the 'Home' card. The system user can enter any module by clicking the module icon on the

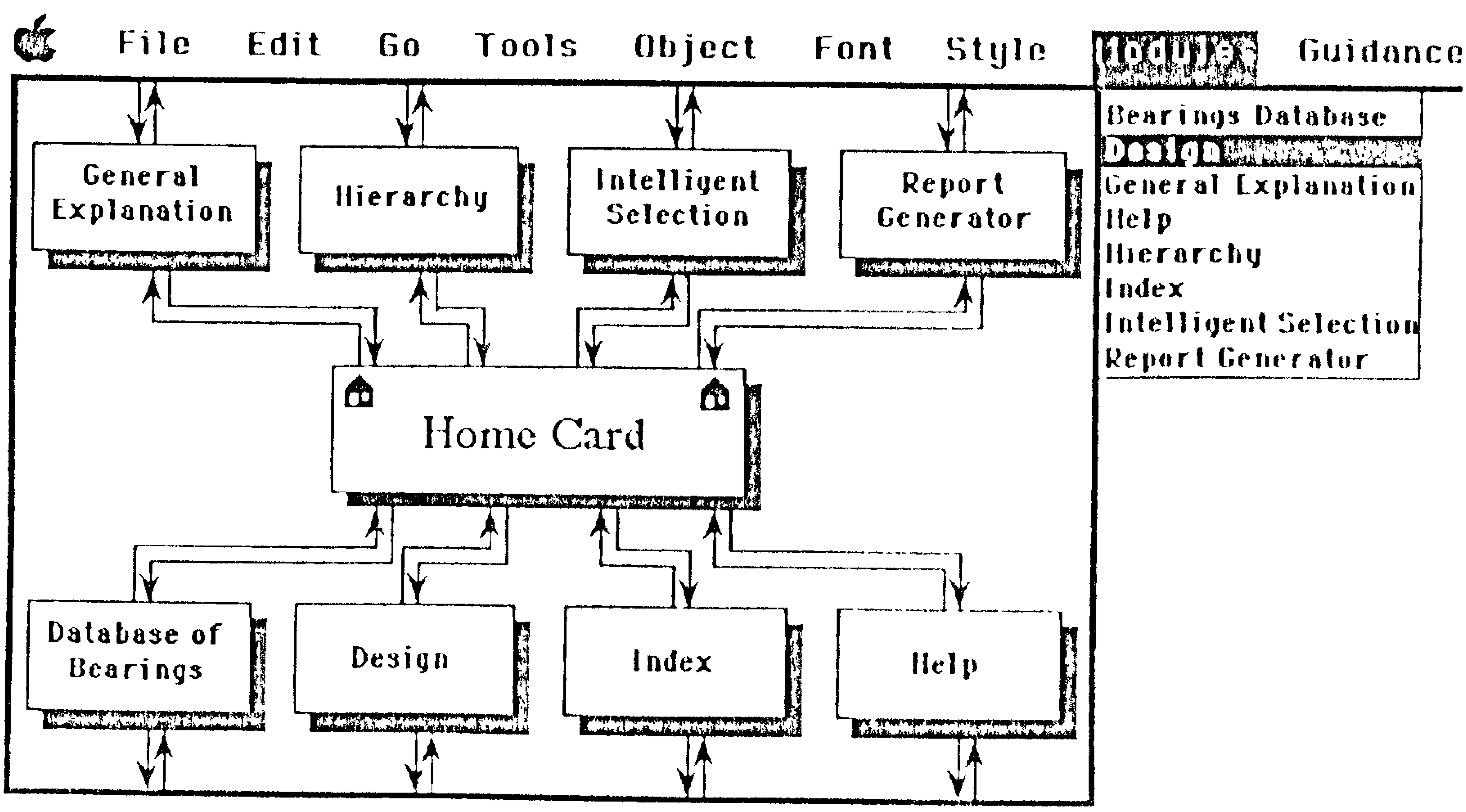


Figure 5.3 The diagram of the system basic framework

'Home' card with a mouse. The system user can also go or jump, from one module to any other module by using a pull-down menu. When any module is opened, the system presents the appropriate pull-down menus which provide a short-cut route for the user to rapidly access any part of the module. Each module is represented as a stack within the HyperCard structure and is easily expanded by adding cards. Each module is designed to be less than 1 MB in memory. The modular structure allows the system to be modified, updated, and distributed using floppy disks.

5.3.2 Linking general language programmes with the system

The scripting language HyperTalk is a versatile programming language. In developing a powerful engineering support system, HyperCard has limitations such as non object oriented programming, limited speed of operation and limited complexity of computing commands. However, the HyperCard environment has an external interface through which new HyperTalk commands (XCMD's) and functions (XFCN's) written in general languages such as C or Pascal can be linked with the environment. Once created, XCMD's and XFCN's can be executed like any other standard HyperTalk command or function inside HyperCard. XCMDs and XFCNs can overcome the limitations in flexibility and programming capacity which are normally accompanied with software system development tools. Figure 5.4, illustrates the principle of linking XCMD's or XFCN's with HyperCard's internal structure.

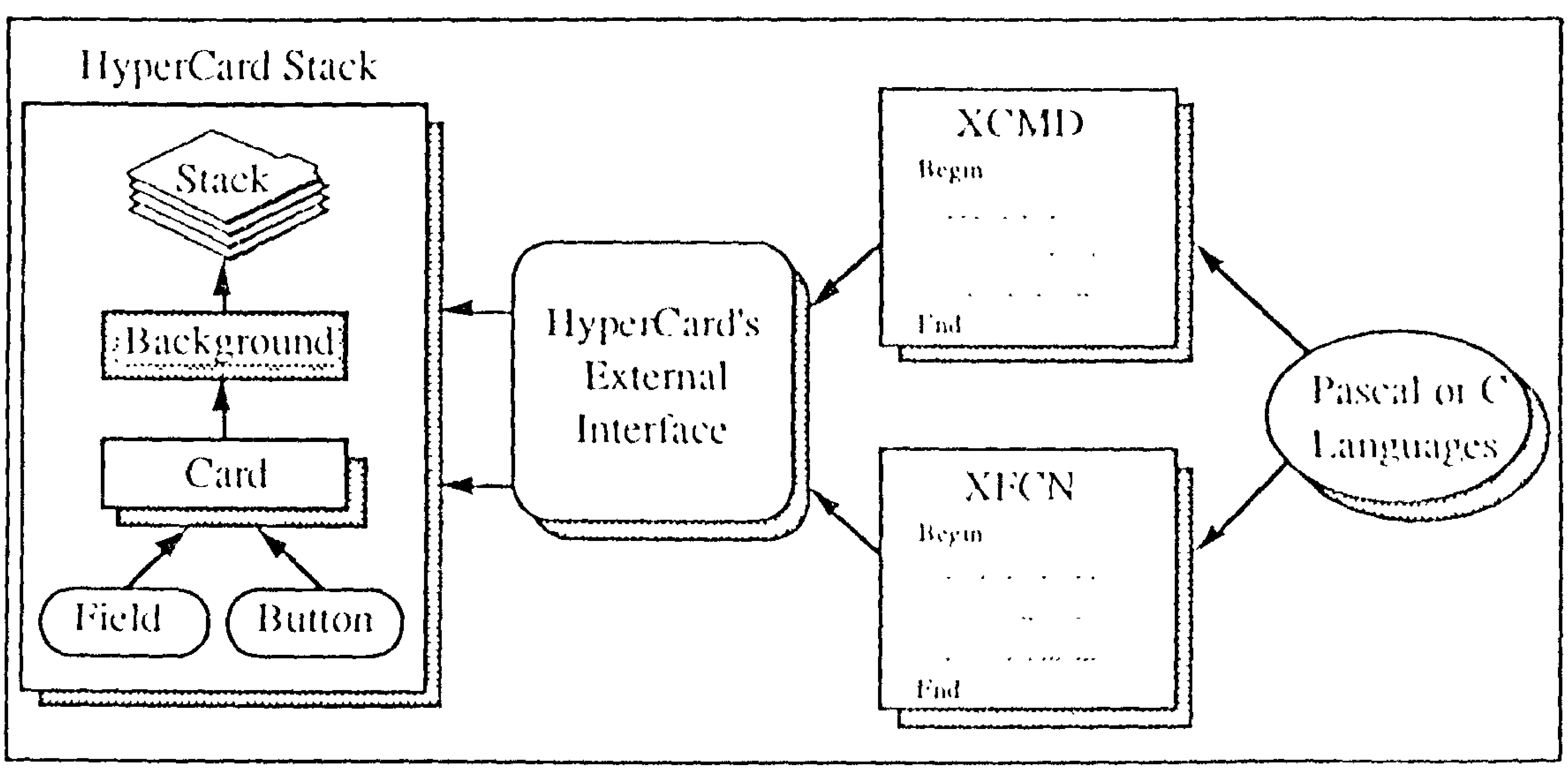


Figure 5.4 Linking XCMDs or XFCNs with HyperCard's internal structure

XCMD's and XFCN's have a wide range of uses. For example, they can be used for the following purposes[81]:

- Adding menus to the HyperCard menu bar,
- Replacing the HyperCard menu bar,
- Animating objects in real time,
- Sorting the contents of a field,
- Creating pop-up menus,
- Making HyperCard talk with other software or environments,
- Improving HyperCard operating speed in mathematical operations.

XCMD's for adding menus to the HyperCard menu bar and replacing the HyperCard menu bar have been incorporated into the system as required so far. The XCMD's are written in Macintosh Workshop Pascal.

5.5 System implementation

The system was developed on a Macintosh IIci computer. However, the system package can be operated on all types of Apple Macintosh computers, but needs the HyperCard 2.0 version and Macintosh System 6.0.5 or later to support it. The total system requires 2.5 MB of memory.

Chapter 6 The functional modules

6.1 The intelligent selection module

6.1.1 Module structure

The intelligent selection module is a knowledge-based system[82]. Figure 6.1, shows

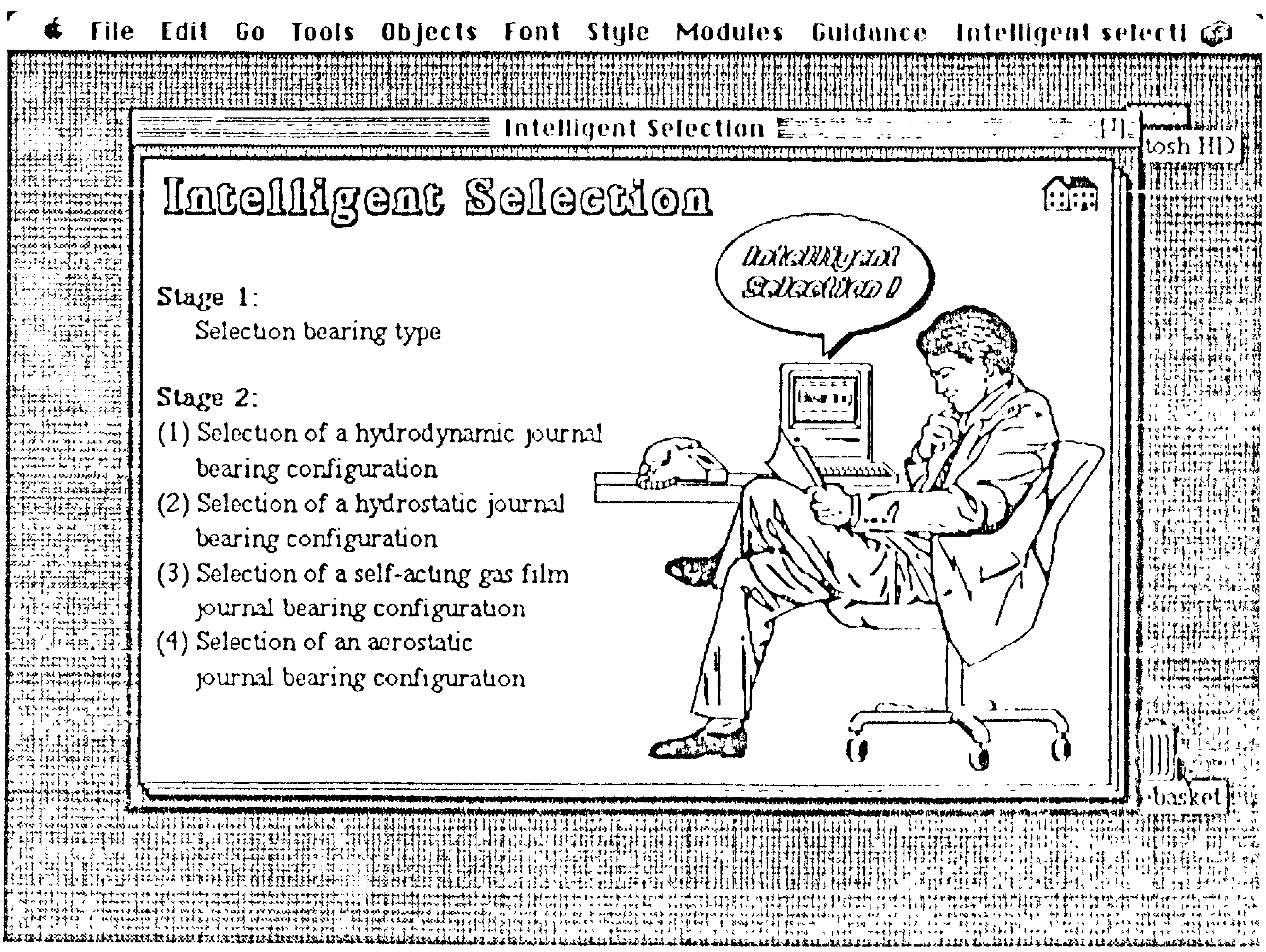


Figure 6.1 The menu card of the intelligent selection module

the menu card of the module. With this module, the user carries out the selection of the bearing type at the first stage and the bearing configuration and fluid feeding type at the second stage. The basic framework of the module is illustrated in Figure 6.2. The module is mainly composed of three parts these being the knowledge base, the inference engine and the user interface. Through the interface, a user or designer can interact with the module to specify the design requirements. Based on the specified requirements, the module makes inferences through the knowledge base to arrive at an optimum selection of the bearing type and then the selection of the bearing configuration and the fluid feeding type. Advice on selection is provided to the user through the interface. Characteristically, of a knowledge-based system, the development of the module involves the processes of knowledge acquisition, knowledge representation and programming, and interface design.

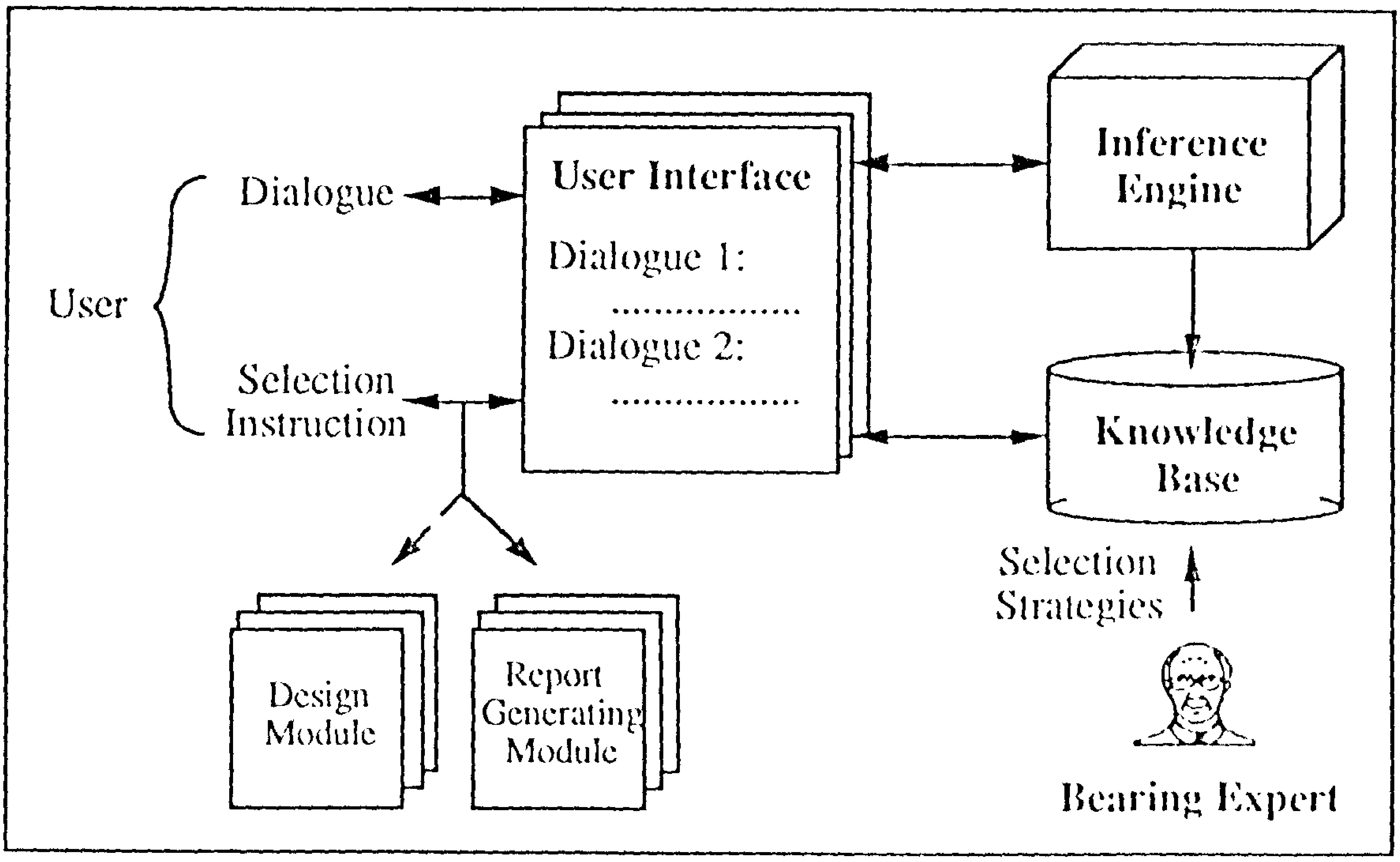


Figure 6.2 The basic framework of the intelligent selection module

6.1.2 Knowledge acquisition

The basic knowledge for the bearing selection was collected and refined from a number of authoritative information sources such as ESDU design data[34], The Tribology Handbook[83], and other publications[2][22][23][30]. Based on knowledge acquisition, the bearing selection strategies were developed as described in section 4.3. The selection strategies form the basis for development of the module. In order to develop a knowledge-based selection system, the selection strategies have to be represented through a knowledge engineering approach. The knowledge acquisition process involves the development of the selection strategies and the modification of the strategies into knowledge to be used by the system.

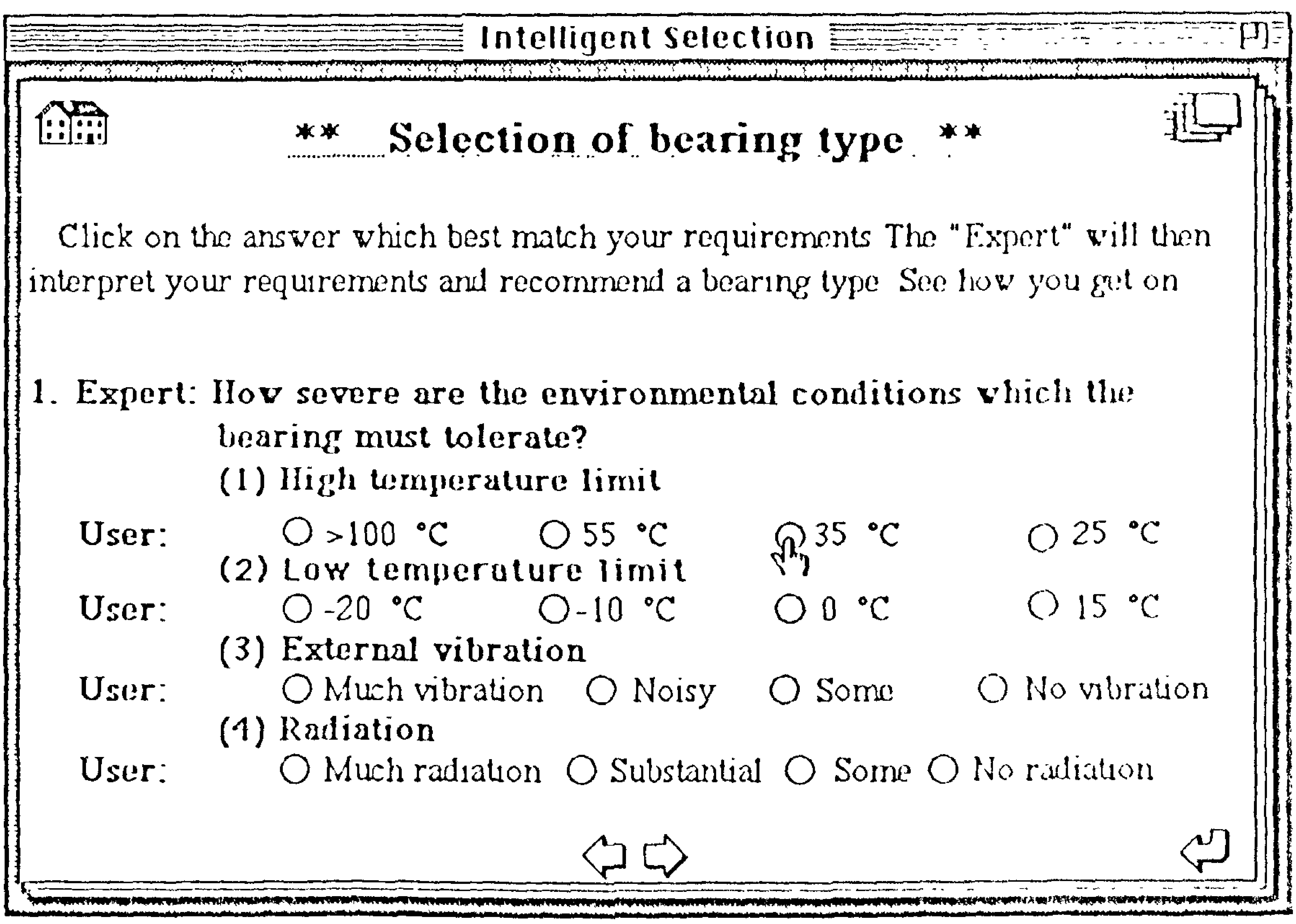
6.1.3 Knowledge representation and programming

Knowledge representation and programming is a kernel process to develop the module, which covers the development of the knowledge base, the inference engine and the user interface.

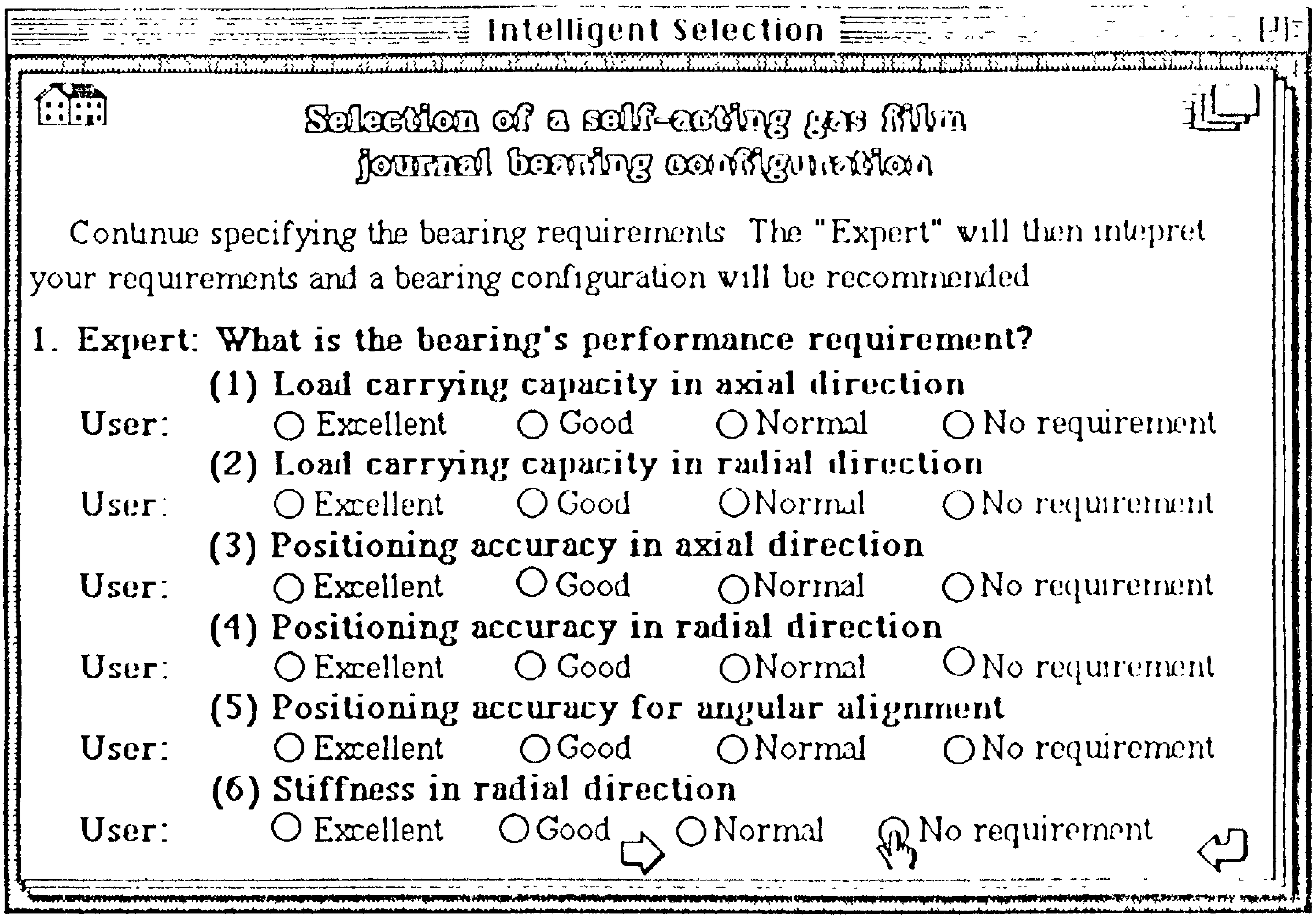
(1) Knowledge base

The knowledge base is based on the 'Production Rules' technique. In order to cope with uncertainty and be able to search the knowledge base as quickly as possible, each production rule is specified with a corresponding weight number as required for the process of selective reasoning.

Each rule is associated with a question and several possible answers. Both the questions and the answers are predefined and explicitly written on the cards as shown in Figure 6.3. In general, for one question, there are three or four answers from which



(a) A card at the first selection stage



(b) A card at the second selection stage

Figure 6.3 Questions and corresponding answers on the module cards

the user may make a single choice by clicking with a mouse. The module takes each question and answer pair as an 'if-then' logic rule. For example, for question 1-(3) on the card shown in Figure 6.2-(a), the module interprets the four question-answer pairs as if the following logic rules and the corresponding weight numbers applied:

(a) **If** external environment condition is much vibration,
Then hydrostatic bearing recommended.

(b) **If** external environment condition is noisy,
Then hydrostatic bearing and aerostatic bearing recommended.
A hydrostatic bearing is given a weighting of 0.6, and an aerostatic bearing a weighting of 0.4.

(c) **If** external environment condition is some vibration,
Then self-acting gas bearing not recommended.
A hydrostatic bearing is given a weighting of 0.4, a hydrodynamic bearing is given a weighting of 0.3 and an

aerostatic is given a weighting of 0.3.

(d) If external environment condition is no vibration,
Then all of the four types of fluid film bearings recommended

Using question and answer pairs is consistent with an expert's normal mental process of decision-making. It is an intuitive and practical way to implement the bearing selection strategy.

The module basically uses the rules for reasoning and searching for the optimum bearing type or bearing configuration and its fluid feeding type. During the reasoning, the system does a computation using the mathematical model discussed in section 4.3.1. This feature allows the module to reason very quickly even where a degree of uncertainty is involved. Weight values sometimes called uncertainty factors are an effective method of coping with the rigidity of reasoning rules in an expert system[84]. For example, for question X_i, the user clicks an answer according to the requirements for the bearing type or configuration B_j. Simultaneously the system responds and gives a corresponding weight number W_{ij} to the question and answer pair. The value of each weighting number W_{ij} is specified based on the rating of the bearing type and configuration discussed in section 4.3. For each bearing type or configuration B_1, B_2, B_3, ..., B_m, a corresponding score can be calculated R_1, R_2, R_3, ..., R_m, where all question and answer pairs X_1, X_2, ..., X_n have the value one.

$$R_1 = X_1 w_{11} + X_2 w_{12} + \ldots\ldots + X_{n-1} w_{1,n-1} + X_n w_{1,n}$$
$$R_2 = X_1 w_{21} + X_2 w_{22} + \ldots\ldots + X_{n-1} w_{2,n-1} + X_n w_{2,n}$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$
$$R_m = X_1 w_{m1} + X_2 w_{m2} + \ldots\ldots + X_{n-1} w_{m,n-1} + X_n w_{m,n}$$

During the dialogue, the user's answers to the questions $\{X_n\}$ define the application requirements for the bearing type or configuration. When the dialogue is finished, the module completes its reasoning and computation and obtains a data dimension $\{R_m\}$. A higher value of R_j takes priority over a lower value. Based on the priority order from the scores R_1, R_2, ..., R_m, the module obtains an optimum selection B_{opt} from bearings [B_m]. The bearing type or configuration B_{opt} is the one with the highest score R_{opt}. Figure 6.4 illustrates a flow chart of the search process.

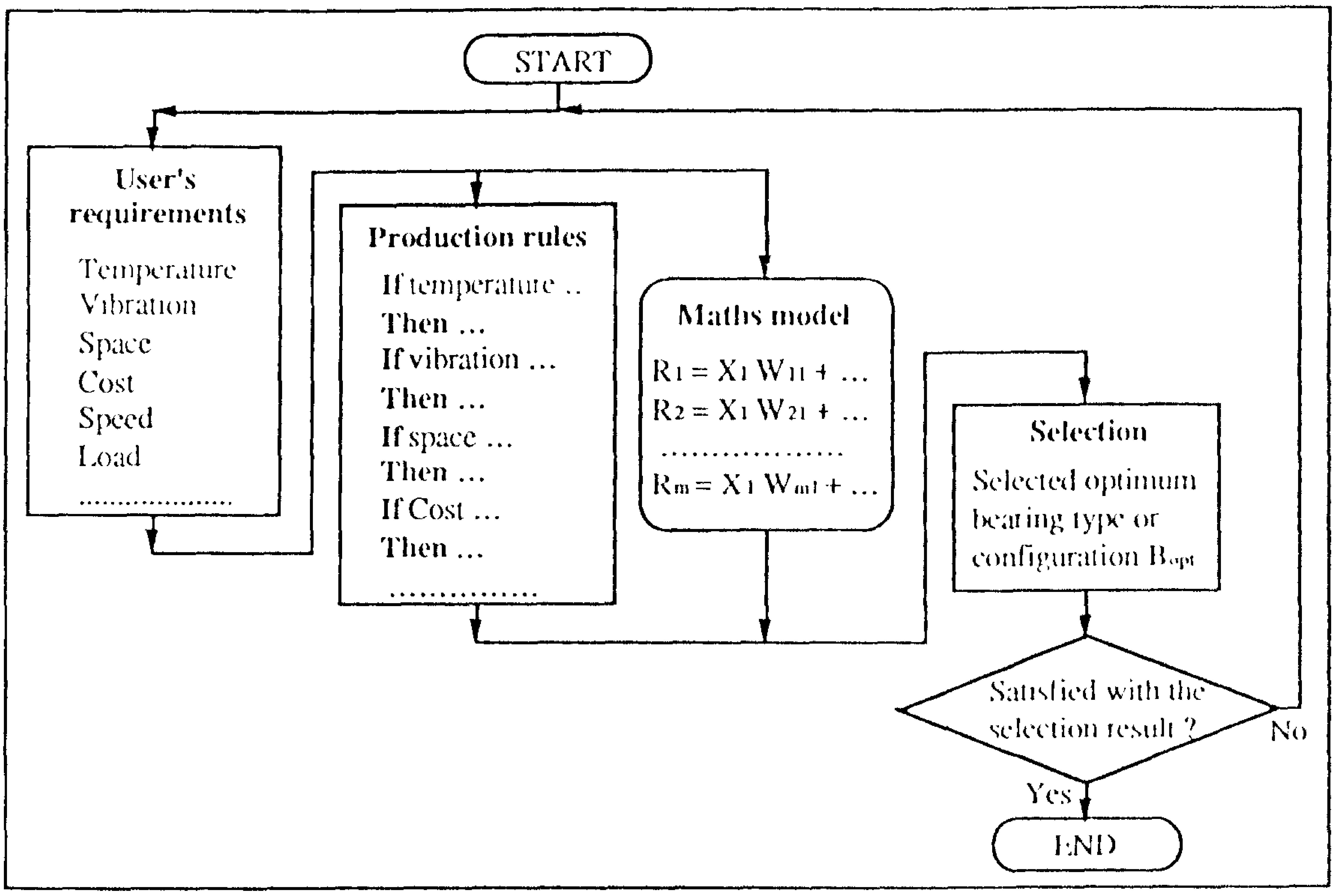


Figure 6.4 Flow chart of the selection searching process

(2) Inference engine

An inference engine is a strategy used to search a knowledge base and logically arrive at a conclusion. In this selection module, as the user clicks each answer values of weights are assigned and the information is thus provided to allow the module to make a decision. The module takes the user's answers, which reflect the design requirements or basic application ideas, as a starting point for the commencement of reasoning and searching. The user inputs form a forward inference chain unaffected by the order of the user's inputs. Figure 6.5 demonstrates the operating mechanism of the inference engine which is programmed in HyperTalk.

In order to simplify the inference process, the bearing type and configuration selections are carried out separately in two stages. At the first stage, the system makes a search through the trunks in the domain of hydrostatic or hydrodynamic journal bearings and aerostatic or self-acting gas film journal bearings of the fluid film bearing family tree, and gives one selection from the four types of bearing. Within the selection, the user can ascribe a degree of emphasis on particular design requirements for the bearings to be required. At the end of the first stage the user confirms satisfaction with the bearing selected. The system automatically guides the user onto the second stage. At the second stage, the system makes a further search through the branches of the bearing family tree for a particular bearing configuration and its fluid feeding type. As in the first stage, the user can place a degree of emphasis on various design requirements. Dividing the selection process into two selection stages and allowing the user to interact with the inference process makes the design and implementation of the inference engine straight-forward.

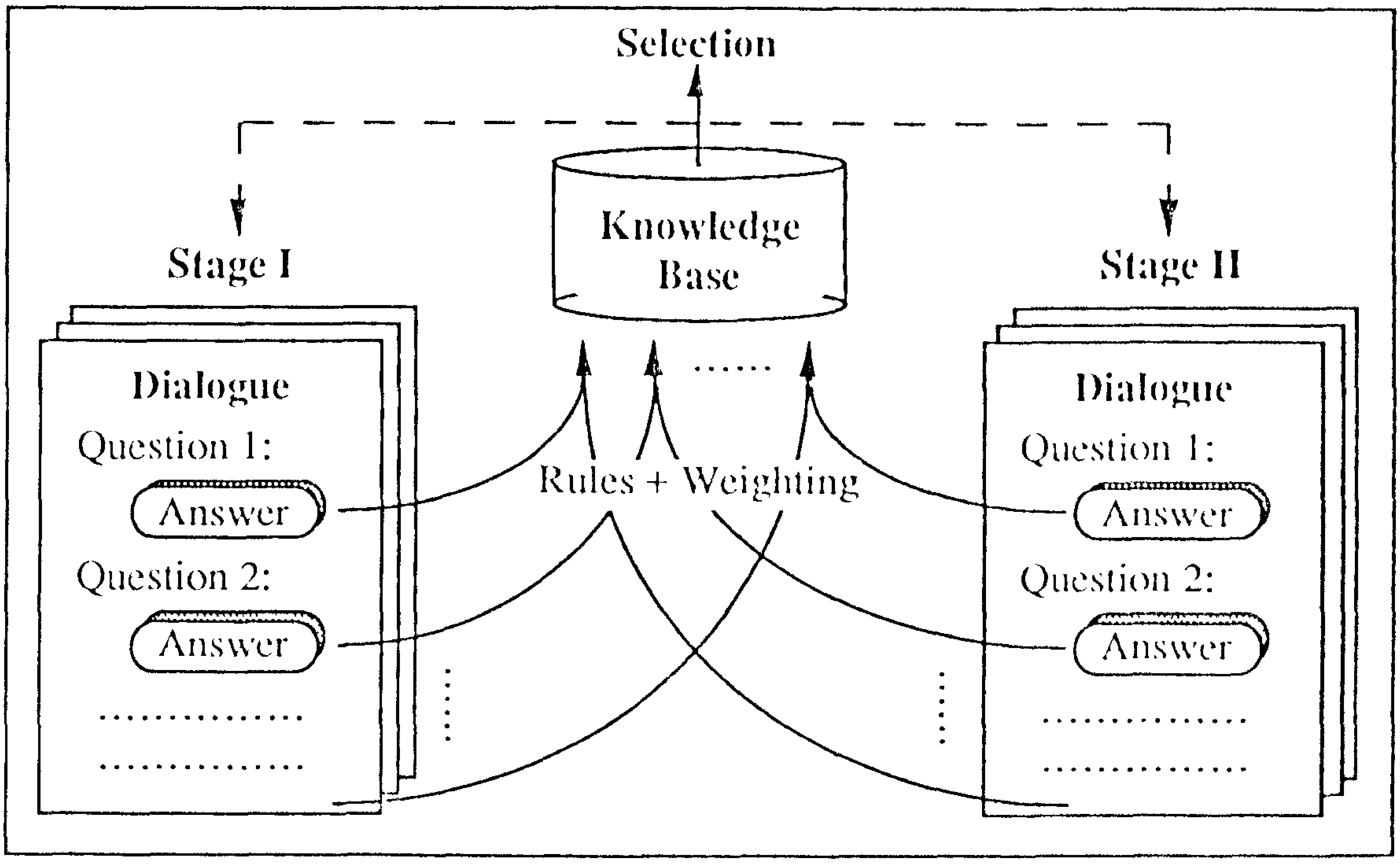


Figure 6.5 The operating mechanism of the inference engine

(3) The User interface

The user interface is constructed in the form of a dialogue between the module and the user as previously described. The process is carried out by the user clicking selected answers with a mouse. Figure 6.6 shows part of the dialogue process for the selection

Intelligent Selection

Intelligent selection of an aerostatic journal bearing configuration

Now continue your selection by further dialogue with the "Expert" When the "Expert" understands your requirements, you will be recommended a configuration of bearing for your special purpose

1. **Expert: What is the bearing's performance requirement?**

(1) Load carrying capacity in axial direction

User: ○ Excellent ◉ Good ○ Normal ○ No requirement

(2) Load carrying capacity in radial direction

User: ◉ Excellent ○ Good ○ Normal ○ No requirement

(3) Positioning accuracy in axial direction

User: ○ Excellent ◉ Good ○ Normal ○ No requirement

(4) Positioning accuracy in radial direction

User: ◉ Excellent ○ Good ○ Normal ○ No requirement

(5) Positioning accuracy for angular alignment

User: ○ Excellent ◉ Good ○ Normal ○ No requirement

(6) Stiffness in radial direction

User: ◉ Excellent ○ Good ○ Normal ○ No requirement

(a)

Intelligent Selection

(7) Stiffness in axial direction

User: ○ Excellent ◉ Good ○ Normal ○ No requirement

2. **Expert: What is the requirement for the bearing's production cost, ease of design and ease of manufacture?**

(1) Production cost

User: ○ Lowest cost ◉ Normal cost ○ No requirement

(2) Ease of design

User: ○ Excellent ◉ Good ○ Normal ○ No requirement

(3) Ease of manufacture

User: ○ Excellent ◉ Good ○ Normal ○ No requirement

3. **Expert: What are the bearing's performance requirements?**

(1) Self-aligning ability

User: ○ Excellent ◉ Good ○ Normal ○ No requirement

(2) Combined axial and radial load carrying ability

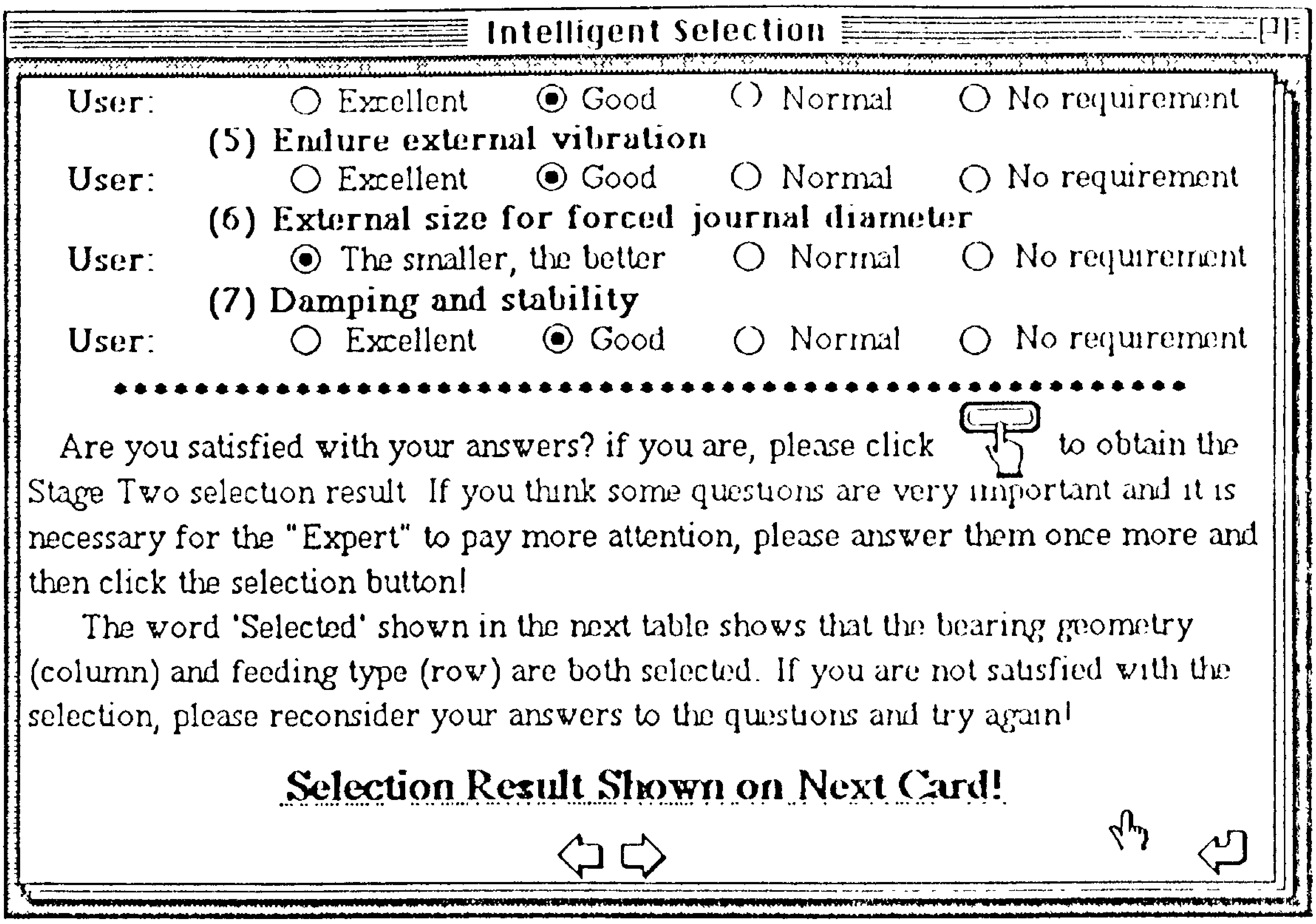
User: ◉ Excellent ○ Good ○ Normal ○ No requirement

(3) Ease of maintenance

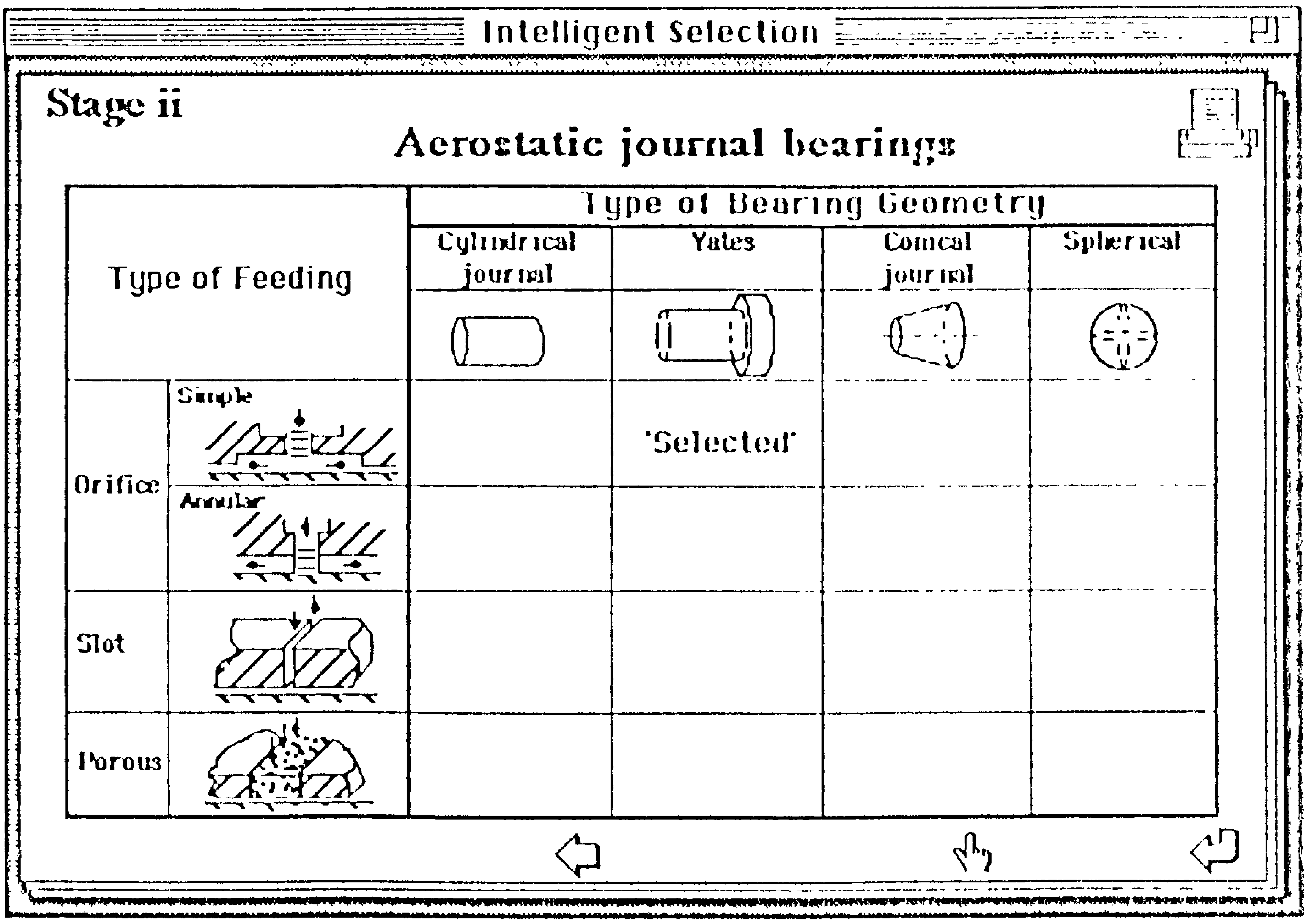
User: ○ Excellent ◉ Good ○ Normal ○ No requirement

(4) Economy of flow rate, power and number of parts

(b)



(c)



(d)

Figure 6.6 Part dialogue process shown on the module cards of an aerostatic bearing configuration. When an answer is chosen by clicking the appropriate answer button, the button is highlighted. When the dialogue is finished, the user can click the system selection button and obtain the system's recommendation. On the module cards, there are various kinds of browsing buttons such as 'home', 'return', 'last' and 'next' button which allow the user to move from one card to another within the module or go to the system menu card. The user can also use the built-in pull-down menus to access different selection stages or other system modules. The user may print the dialogue process or the system selection result, using the 'printer' button on the cards or the system standard pull-down menu.

6.1.4 Implementation

The module is a key part of the design support system. The module can also work as an independent package for bearing selection purposes. The module requires 300 KB of memory as developed so far.

6.2 The design module

6.2.1 Module structure

Figure 6.7, shows the menu card of the design module. The module has been developed by a new method which incorporates AI techniques with the bearing design techniques including numerical computation and optimisation of bearing parameters. As shown in Figure 6.7, the module can be used to design both hydrostatic and aerostatic bearings. The module can also provide design support for the auxiliary devices such as the flow control devices, circuit, liquid tank, and the supply system. The designer can access the two sub-menu cards, as shown in Figure 6.8, by clicking the highlighted titles on the menu card shown in Figure 6.7 or using the pull-down menus. From the sub-menu cards, the designer can enter the design procedure for each particular bearing configuration. While undertaking a design procedure, the designer can use the system pull-down menu to exit the procedure and enter other modules to obtain design knowledge that is available on basic bearing concepts, bearing materials selection,

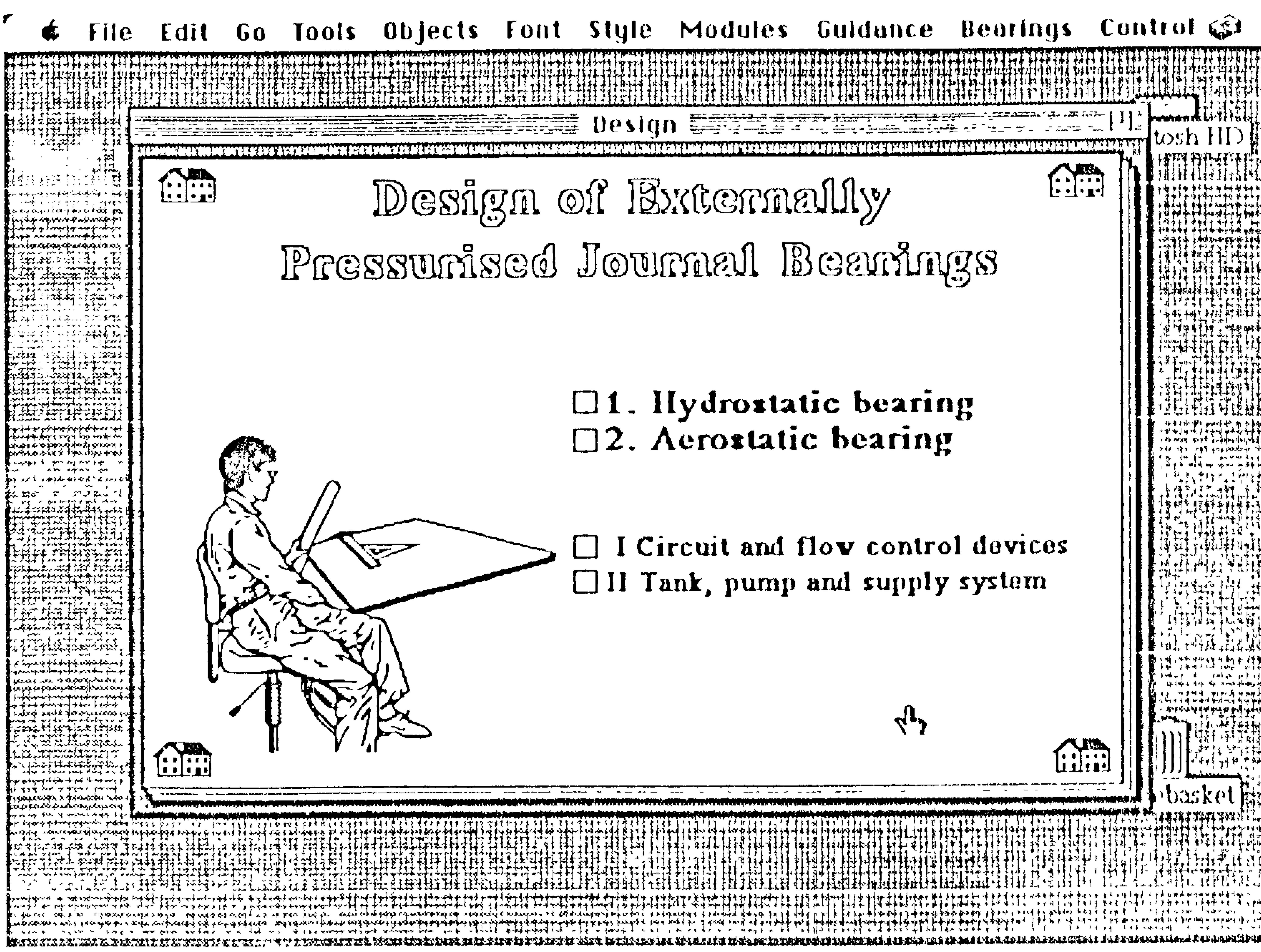
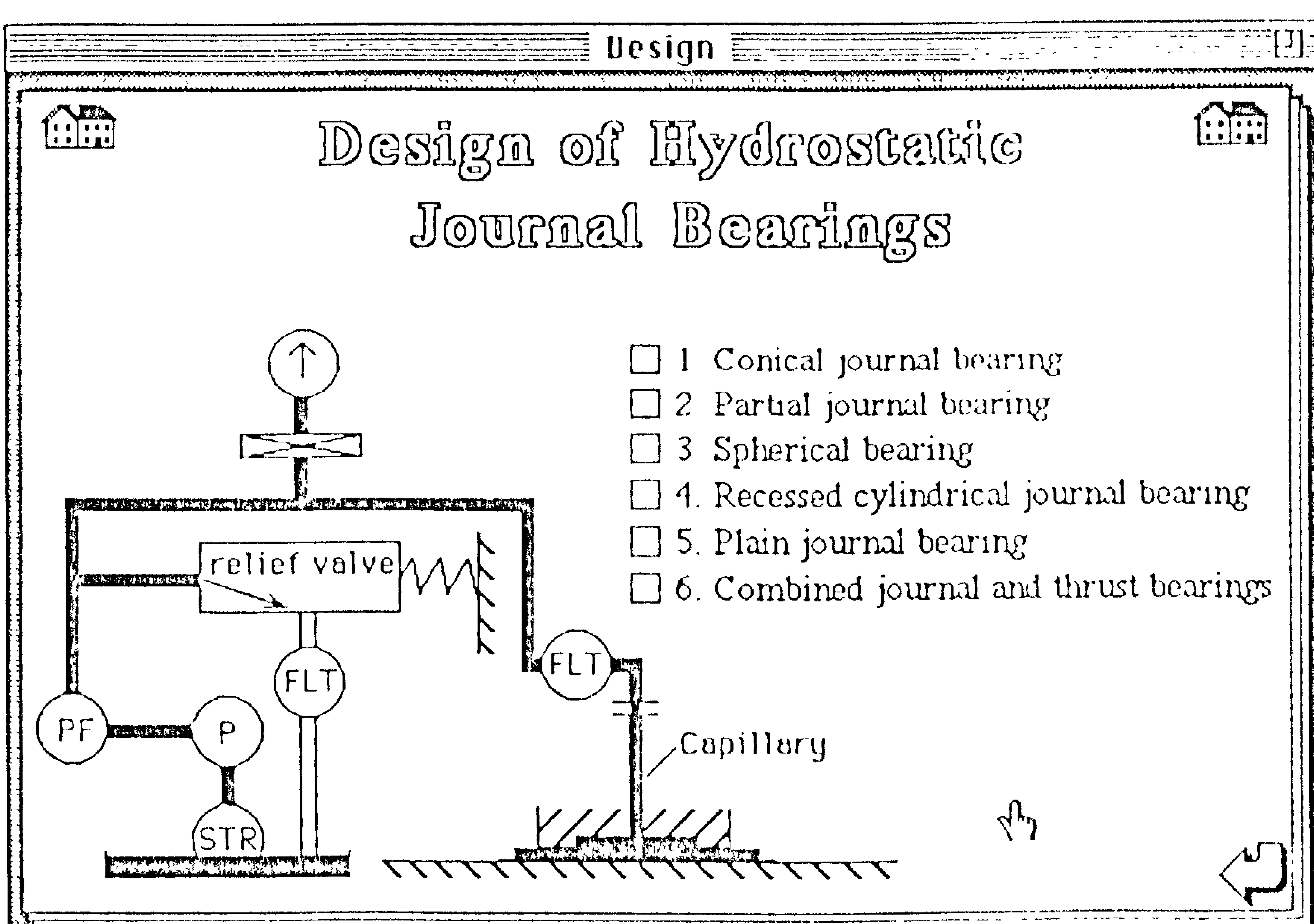
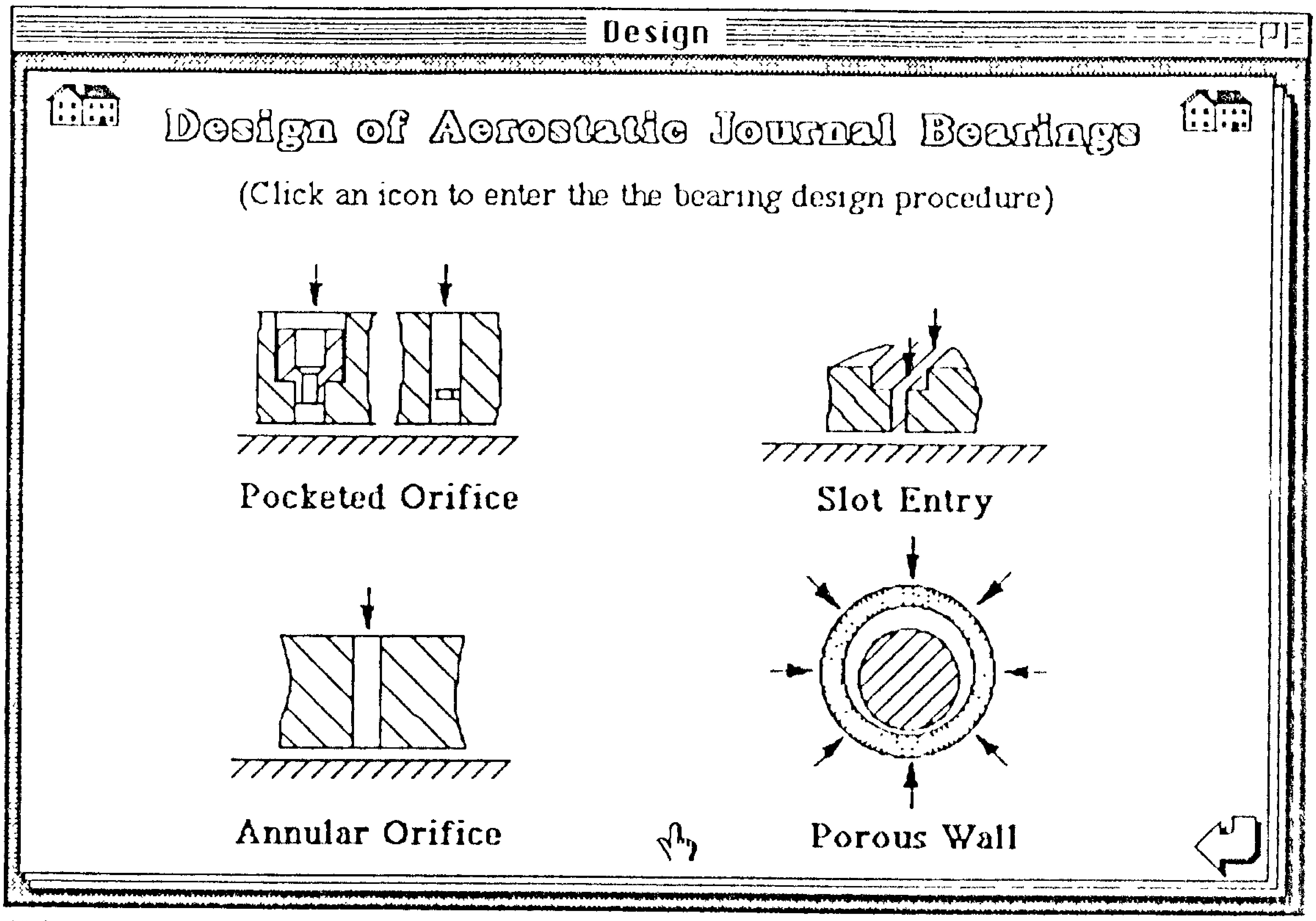


Figure 6.7 The menu card of the design module



(a)



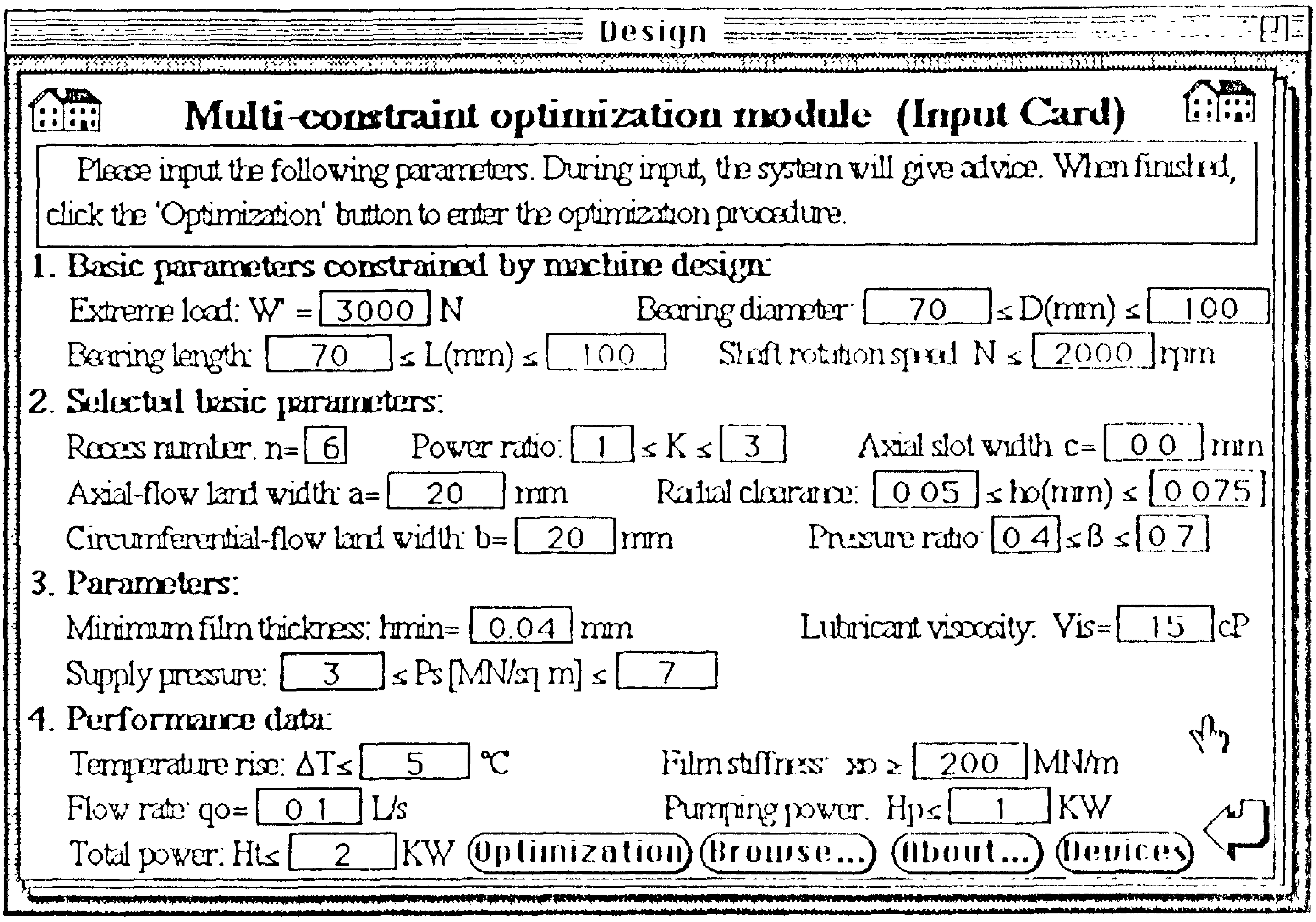
(b)

Figure 6.8 Two sub-menu cards of the design module

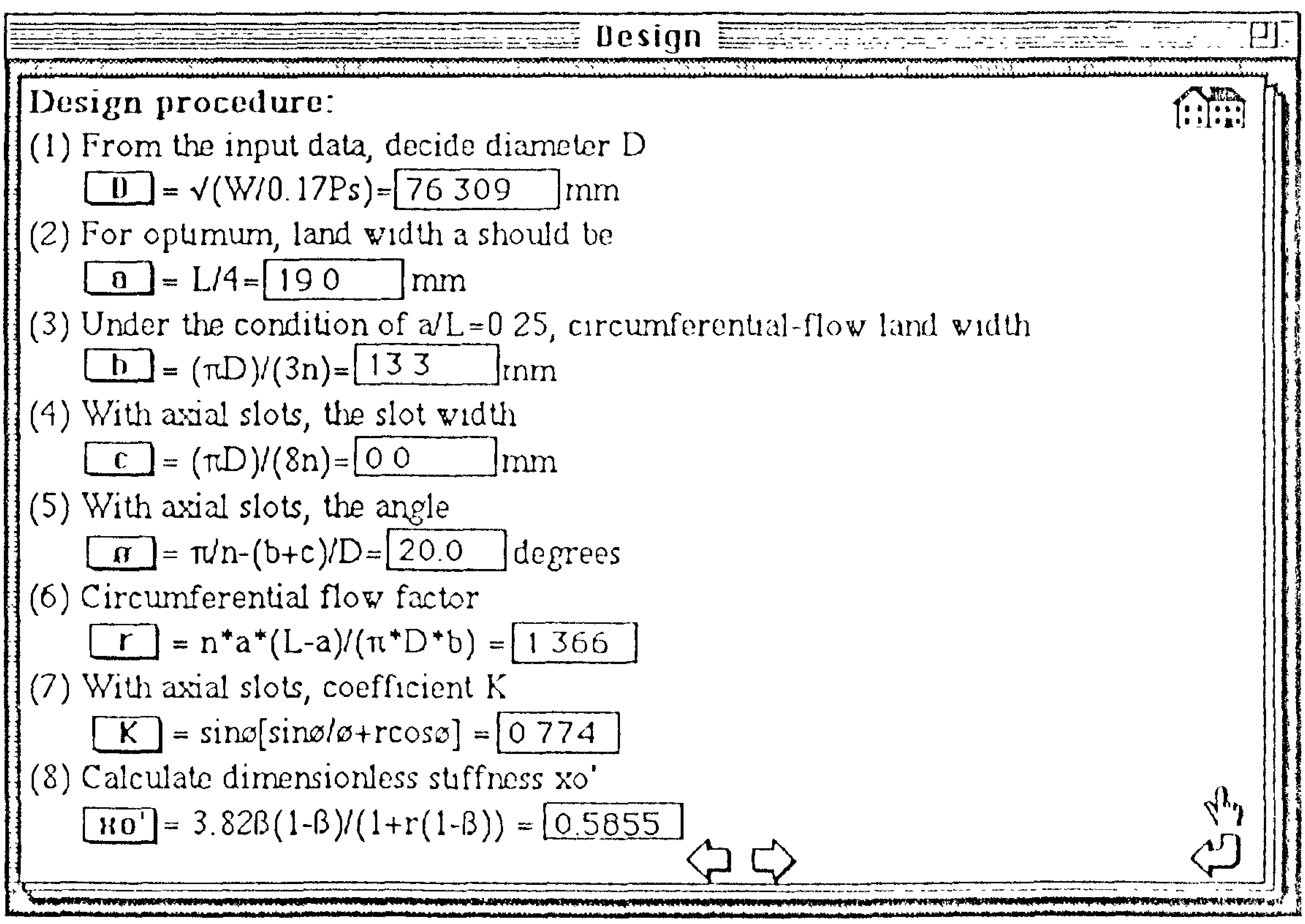
bearing applications, and manufacturing methods. A satisfactory design is achieved not just by using this module but with the operation of the whole system.

6.2.2 Integration of AI

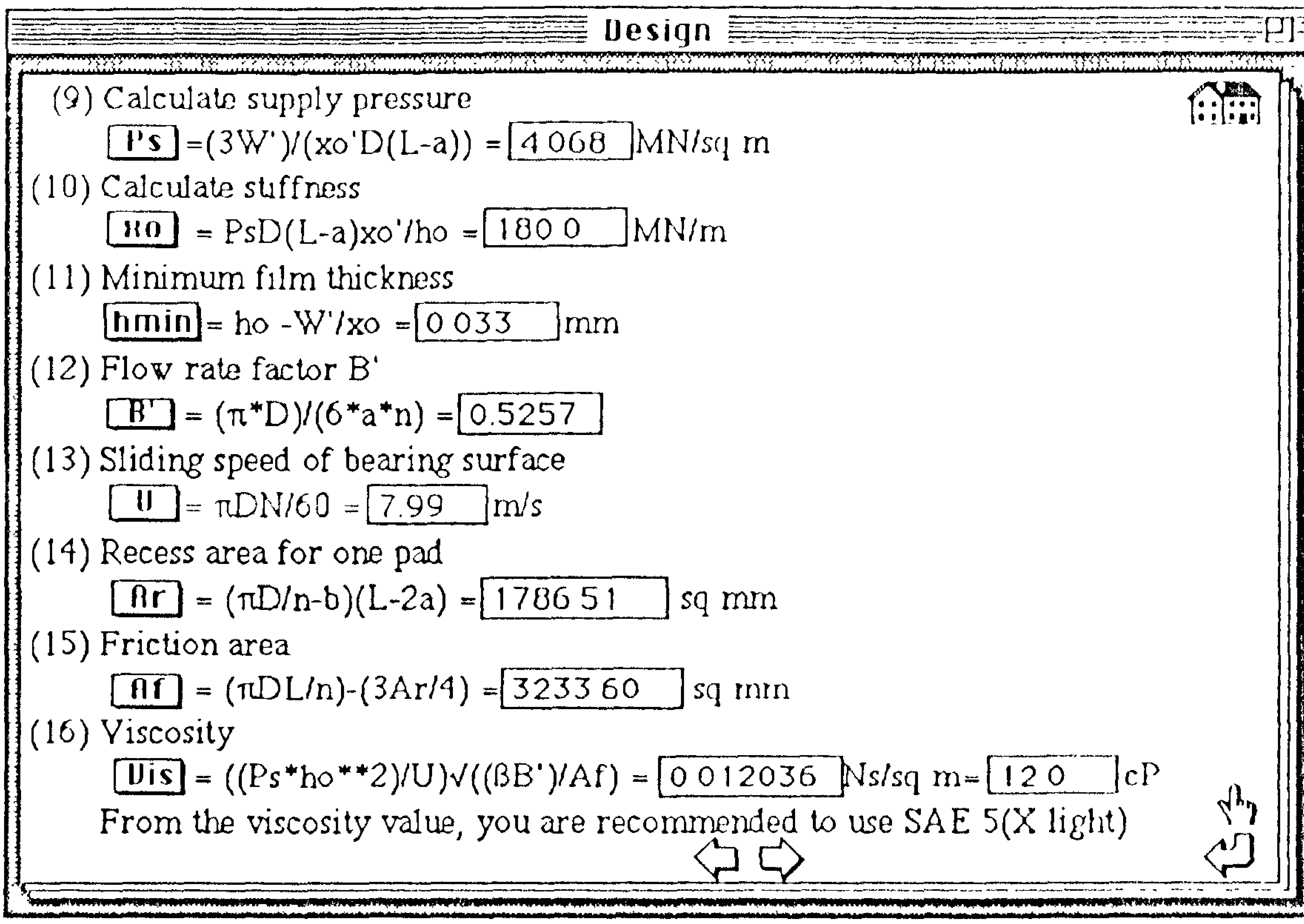
The bearing design approaches described in Chapter 4 provide the knowledge basis to be incorporated into the module. Figure 6.9 (a) to (e) shows the design cards of an optimal design procedure for a hydrostatic bearing. The design procedure is, basically consistent with the design procedure discussed in section 4.4.2, but AI has been integrated into the procedure to take account of both numerical and qualitative issues. For example, AI is integrated with the design procedure for the design compatibility analysis (DCA). The DCA includes the design input analysis, the design process monitoring, and the design output analysis. The AI is rule-based. For example, on card (a) of Figure 6.9, when a designer inputs a value into each parameter value field, the AI associated with each field will make a decision as to whether the input value is within a suitable range. If the value is not suitable, the module will give a warning and



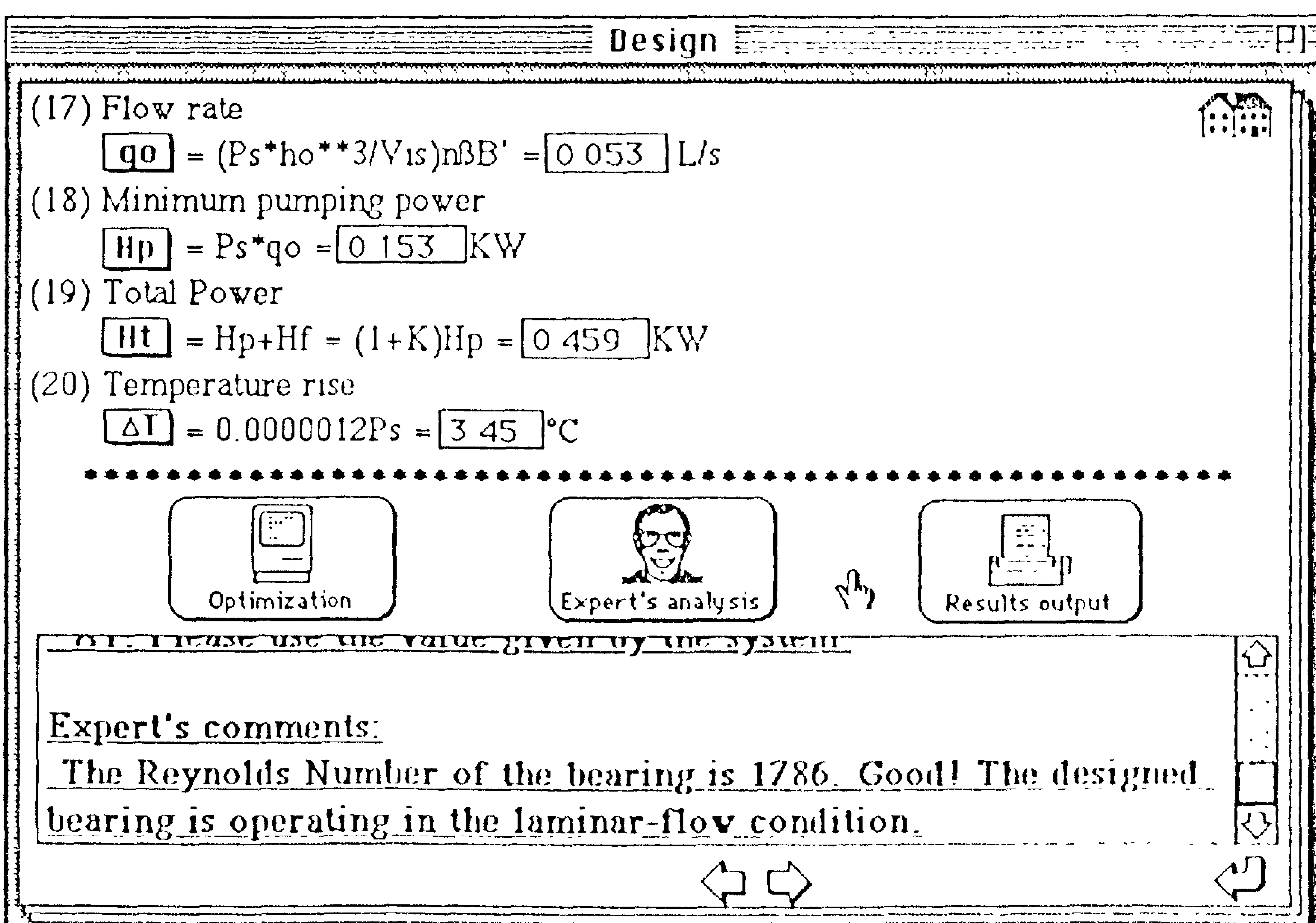
(a)



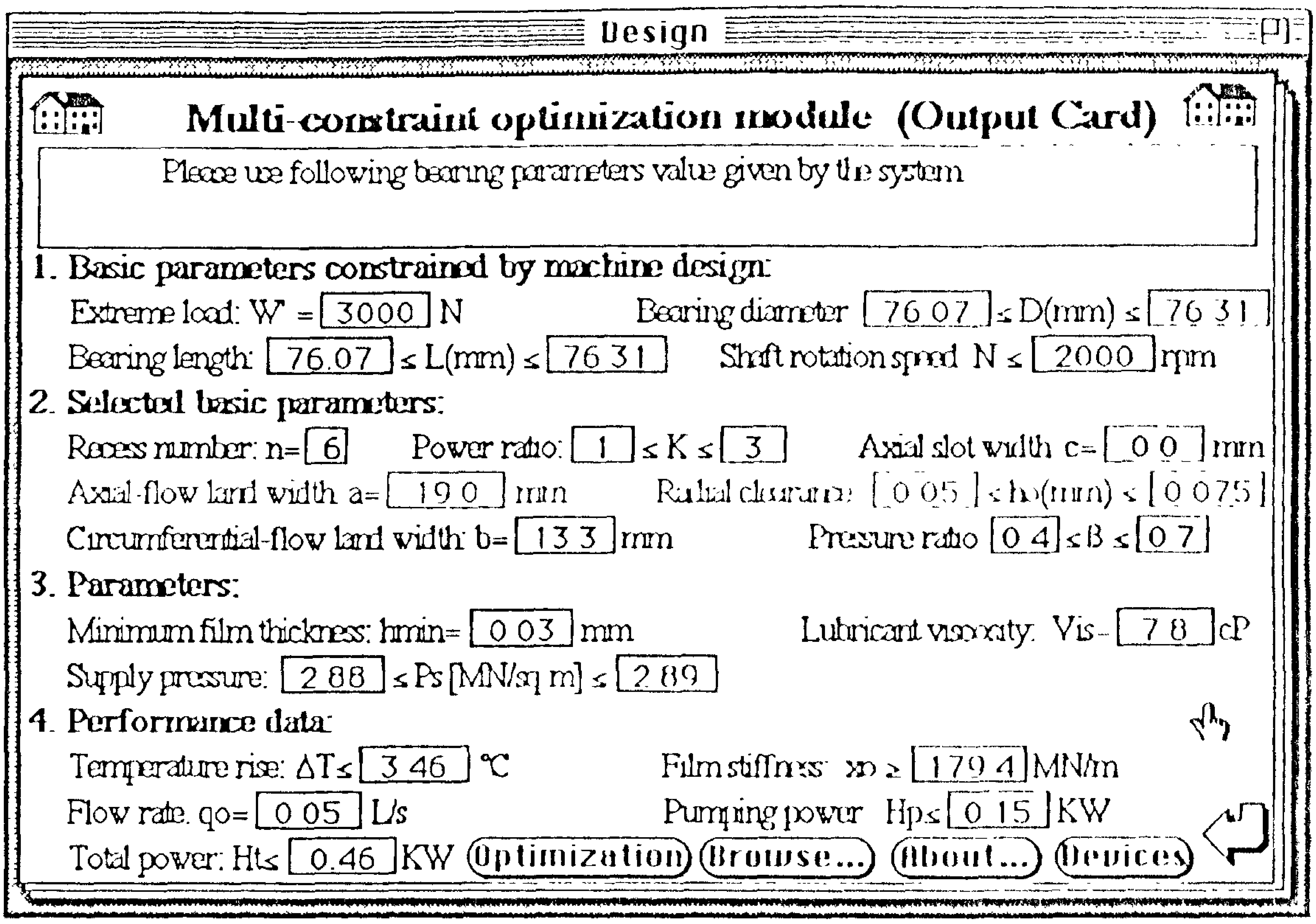
(b)


Design
(9) Calculate supply pressure
Ps =(3W')/(xo'D(L-a)) = 4 068 MN/sq m
(10) Calculate stiffness
xo = PsD(L-a)xo'/ho = 180 0 MN/m
(11) Minimum film thickness
hmin = ho -W'/xo = 0 033 mm
(12) Flow rate factor B'
B' = (π*D)/(6*a*n) = 0.5257
(13) Sliding speed of bearing surface
U = πDN/60 = 7.99 m/s
(14) Recess area for one pad
Ar = (πD/n-b)(L-2a) = 1786 51 sq mm
(15) Friction area
Af = (πDL/n)-(3Ar/4) = 3233 60 sq mm
(16) Viscosity
Vis = ((Ps*ho**2)/U)√((ßB')/Af) = 0 012036 Ns/sq m= 12 0 cP
From the viscosity value, you are recommended to use SAE 5(X light)

(c)


Design
(17) Flow rate
qo = (Ps*ho**3/Vis)nßB' = 0 053 L/s
(18) Minimum pumping power
Hp = Ps*qo = 0 153 KW
(19) Total Power
Ht = Hp+Hf = (1+K)Hp = 0 459 KW
(20) Temperature rise
ΔT = 0.0000012Ps = 3 45 °C
Optimization
Expert's analysis
Results output
Expert's comments:
The Reynolds Number of the bearing is 1786. Good! The designed bearing is operating in the laminar-flow condition.

(d)



(e)

Figure 6.9 Design cards of an optimal design procedure for a hydrostatic bearing

a message in the message field at the top of the card. The programmed rules for the bearing pressure ratio ß is as follows:

```
On MouseEnter
  put "(Input Card)" into card field Locard
  put "A suitable range is 0.4≤ß≤0.7. This range may be ensured by
      the selection of suitable tolerance for the clearance between
      the shaft and bearing." into card field Message
End MouseEnter

On MouseLeave
  put card field pressure ratio into holder
  if holder<0.4 or holder>0.7 then
    put " Please input according to the system suggestion!" into
        card field Message
    play "boing"
    wait 1 second
  else
```

```
    put " Your input may be suitable!" into card field Message
  end if
  put "Please input the following parameters. During input, the
      system will give advice. When finished, click the
      'Optimization' button to enter the optimization procedure."
      into card field Message
End MouseLeave
```

The design process monitoring refers to the compatibility check of practical parameter values during the optimisation process. Each of these parameters are defined with a constraint condition on the input card. During the iterative optimisation, the AI will check whether a calculated parameter value is outside the constraint range. If it is outside the required range, the module will give a warning message for the designer to

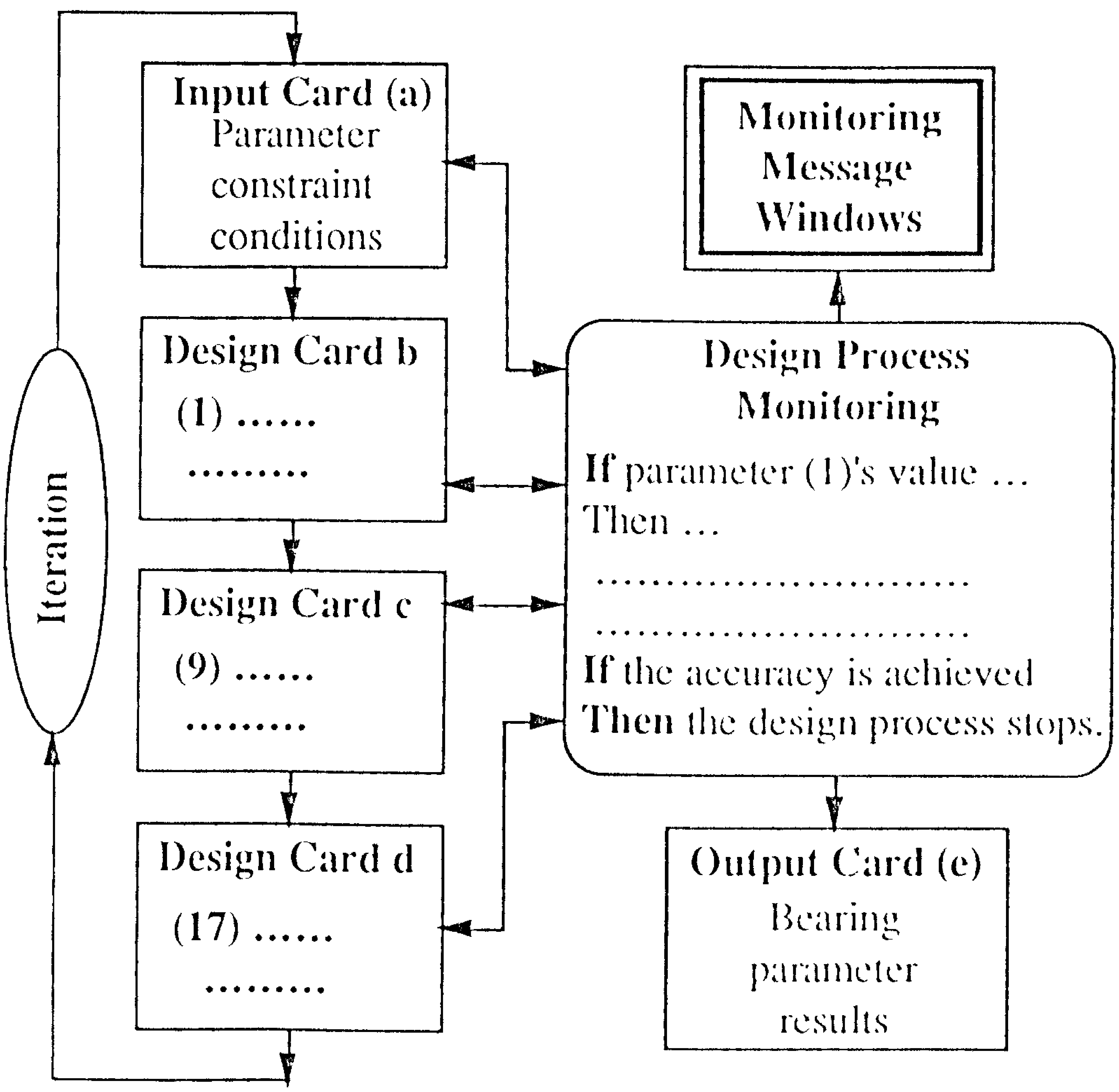


Figure 6.10 The working principle of the design process monitoring

make a change to the input data or continue the operation. The principle of the design process monitoring is illustrated in Figure 6.10.

On design card (d) of Figure 6.9, there is an 'Expert Analysis' icon button. After the design process is finished, the designer can click the button and the module will make a compatibility analysis of the design results on the output card. The analysis includes checking whether each designed value is within the normal permissible range for the design requirements and whether the designed bearing can work in the laminar flow regime. The 'Expert Analysis' is a rule-based program written in HyperTalk.

6.2.3 Implementation

The module has been developed as a key part of the design support system. All design computing procedures and the AI based analysis within the module are programmed in HyperTalk. XCMDs for adding and replacing specific module pull-down menus are incorporated into the module. The XCMDs are written in Macintosh Workshop Pascal. The module requires 1 MB of memory.

6.3 Other functional modules

6.3.1 General explanation module

Figure 6.11, shows the menu card of the general explanation module. The module was developed using hypermedia techniques. The module provides an outline description of externally pressurised journal bearings in the form of text, graphics, tables, and images on the cards. Figure 6.12 illustrates two cards copied from the module. A system user can browse the information by clicking the highlighted contents list or 'next' and 'previous' buttons on the cards, or by using the module pull-down menus. The module can be viewed as a hypertext style electronic book. The module contents are associatively linked with other modules. The information within the module is intended to be useful for an inexperienced bearing designer.

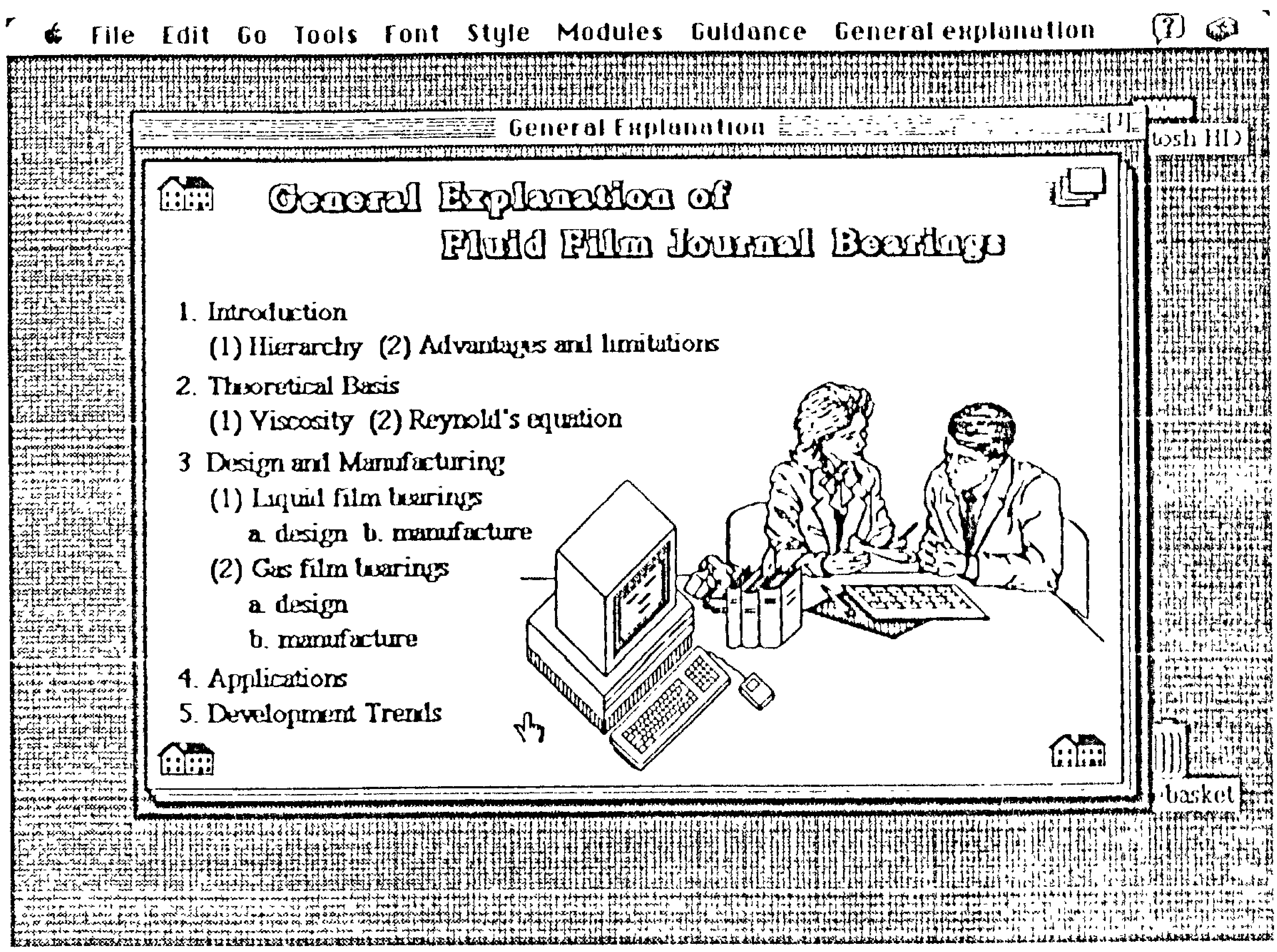
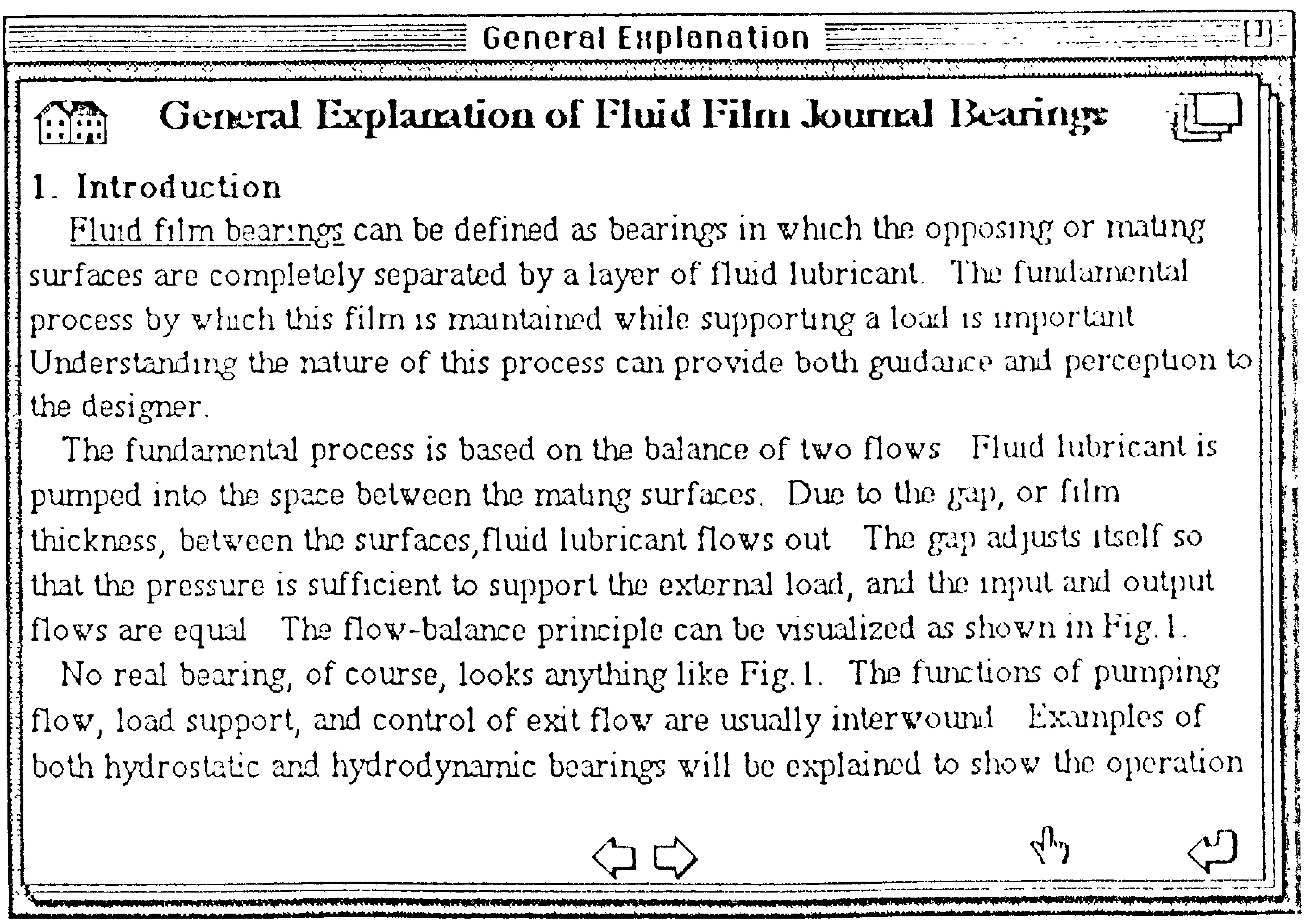
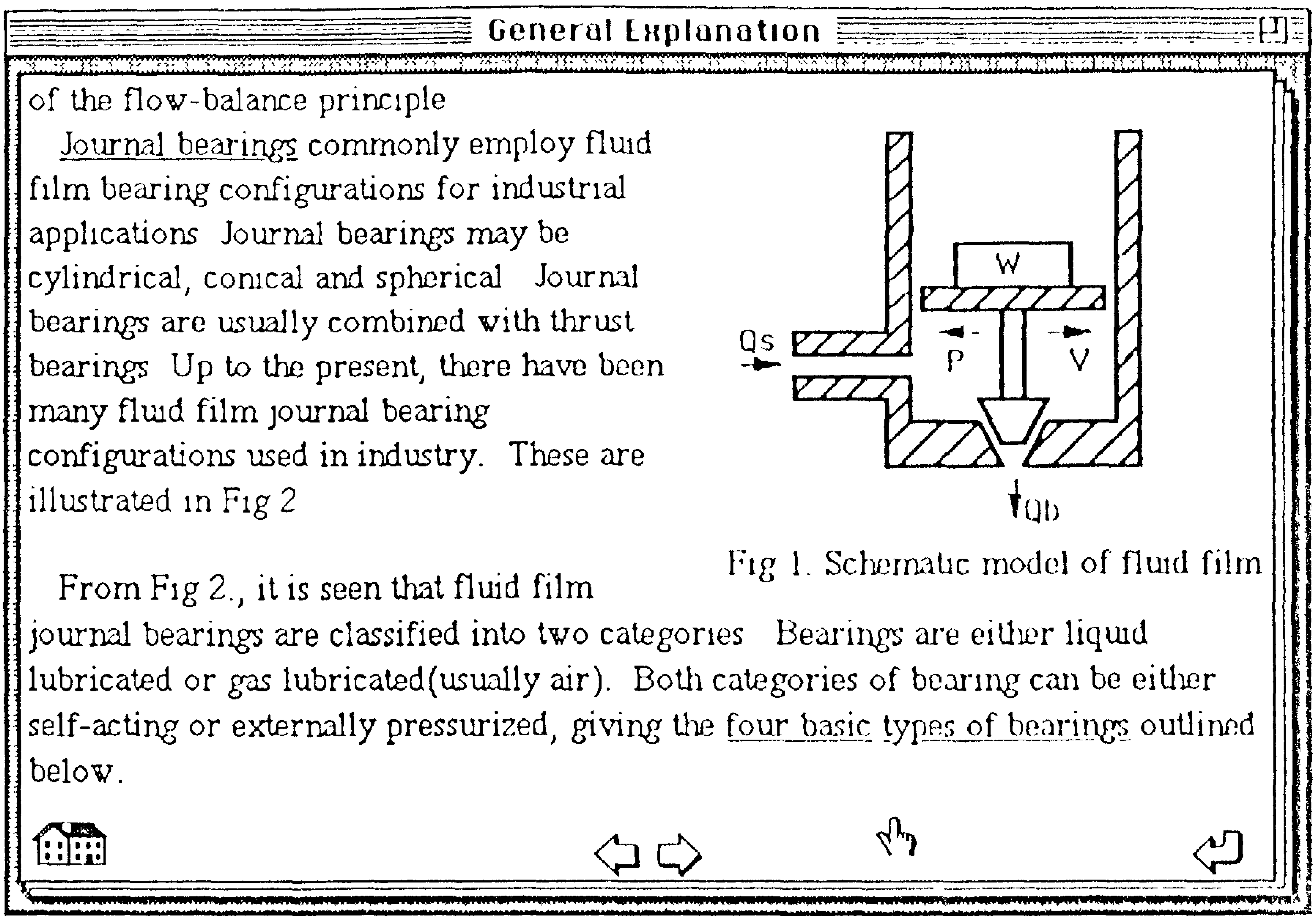


Figure 6.11 The menu card of the general explanation module



(a)


General Explanation

of the flow-balance principle

Journal bearings commonly employ fluid film bearing configurations for industrial applications Journal bearings may be cylindrical, conical and spherical Journal bearings are usually combined with thrust bearings Up to the present, there have been many fluid film journal bearing configurations used in industry. These are illustrated in Fig 2

Fig 1. Schematic model of fluid film

From Fig 2., it is seen that fluid film journal bearings are classified into two categories Bearings are either liquid lubricated or gas lubricated(usually air). Both categories of bearing can be either self-acting or externally pressurized, giving the four basic types of bearings outlined below.

(b)

Figure 6.12 Two examples of cards copied from the general explanation module

6.3.2 The hierarchy module

Figure 6.13, shows the menu card of the hierarchy module. The module includes family trees for the bearing configurations and fluid feeding devices, bearing materials, bearing applications, and the system structure tree. The tree structures are illustrated in Figure 6.14 (a)~(d). A system user can access the different tree cards by clicking highlighted titles on the menu card or by using the module built-in pull-down menu. The tree structures not only demonstrate the trunk-bough-branch-twig relationships inside the bearing family, but are also connected with other system functional and auxiliary modules. A user can click any item on a tree to access the information related with the item. For example,when the user clicks 'Grinding machine' on the gas film bearing application tree shown on card c of Figure 6.14, the module automatically guide the user to a photographic image. The image demonstrates a gas film bearing used in a grinding machine.

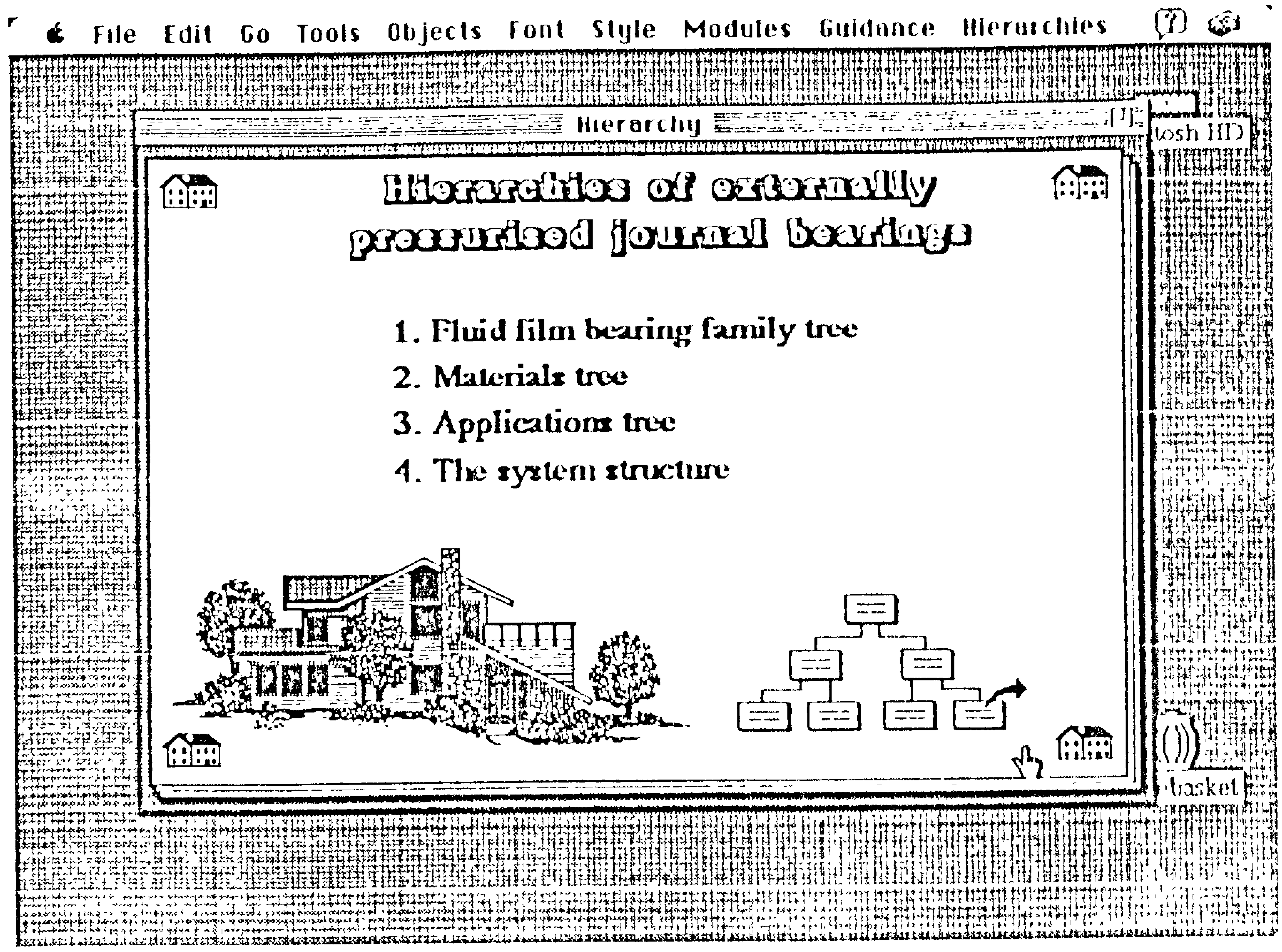
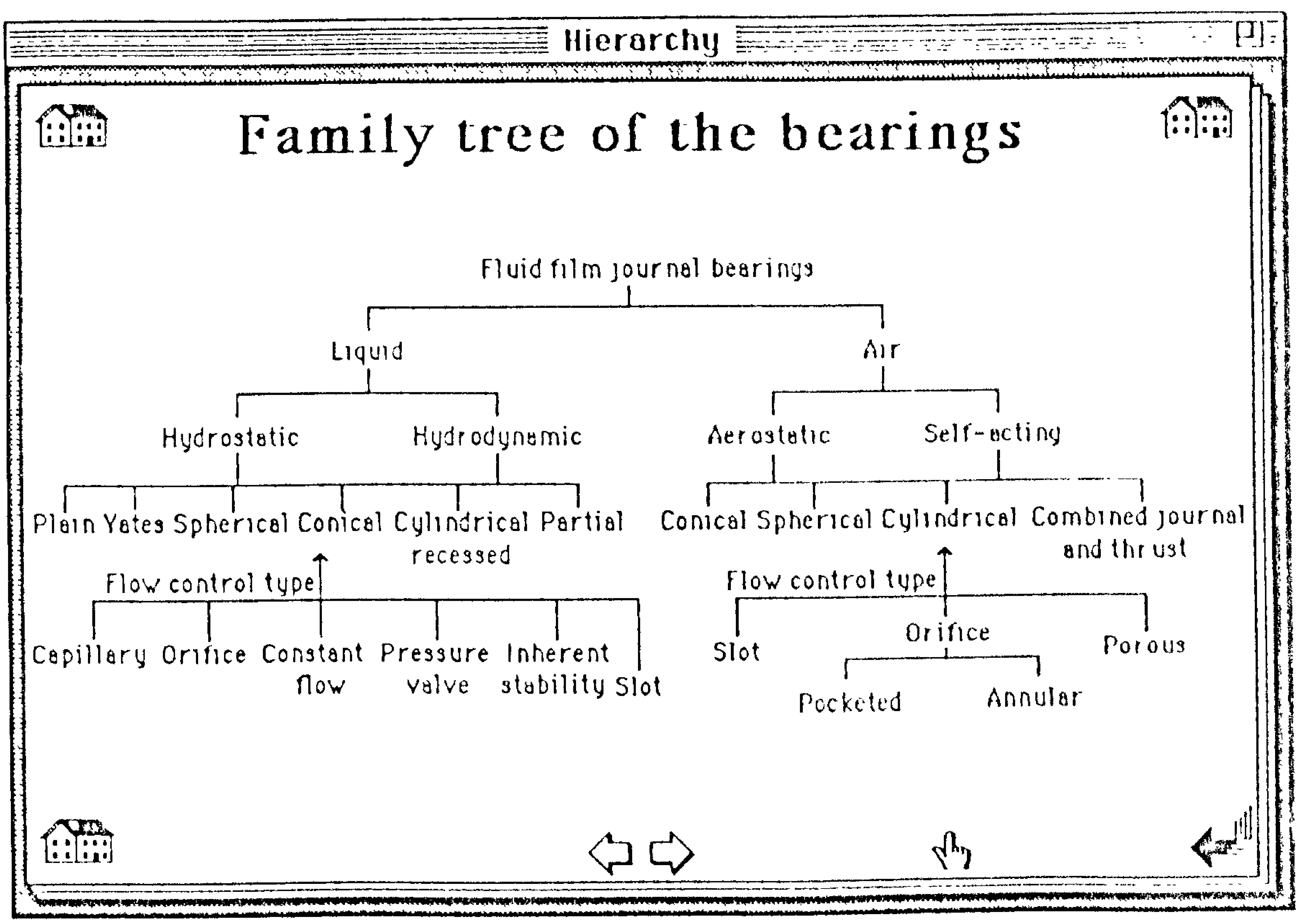
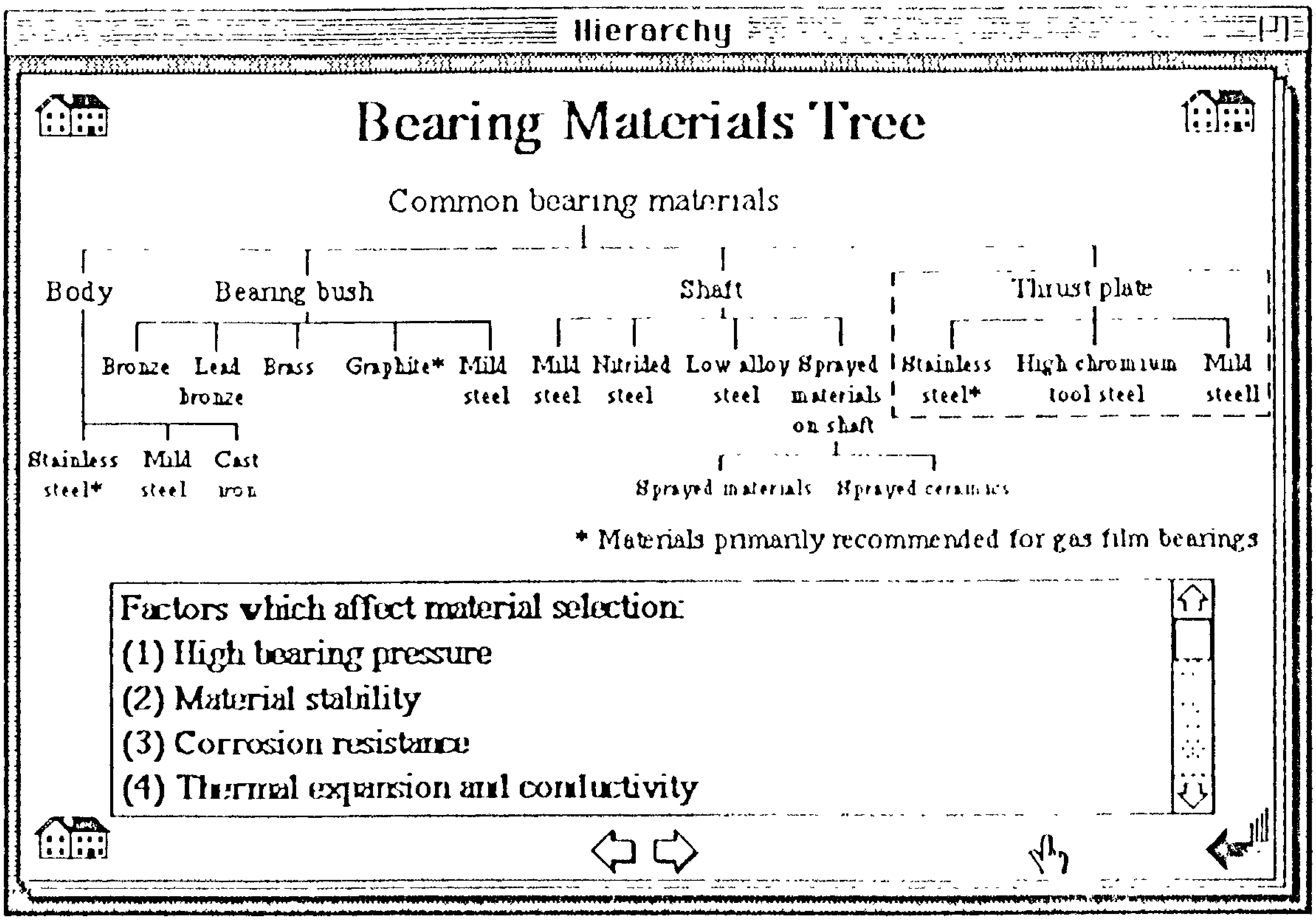


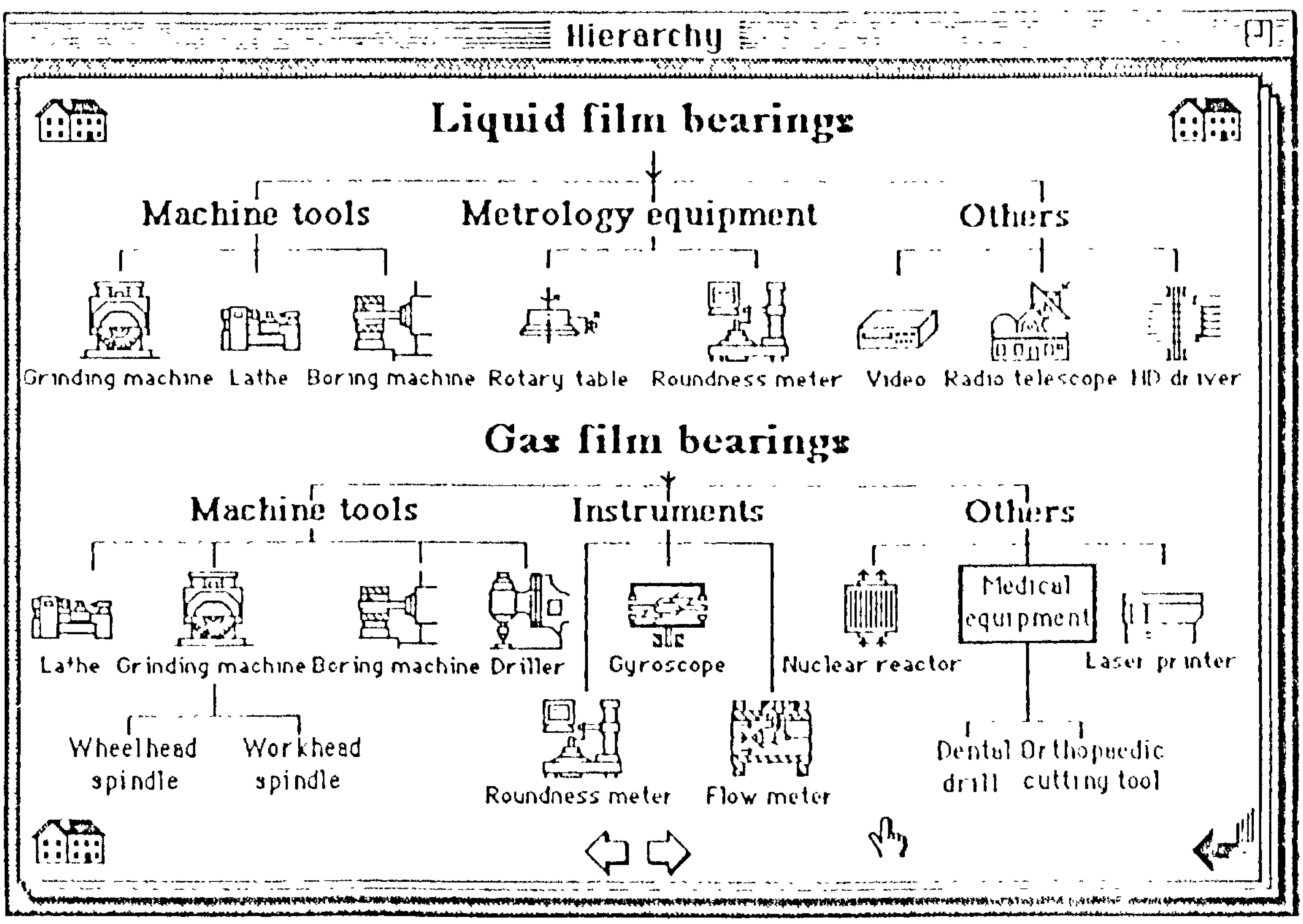
Figure 6.13 The menu card of the hierarchy module



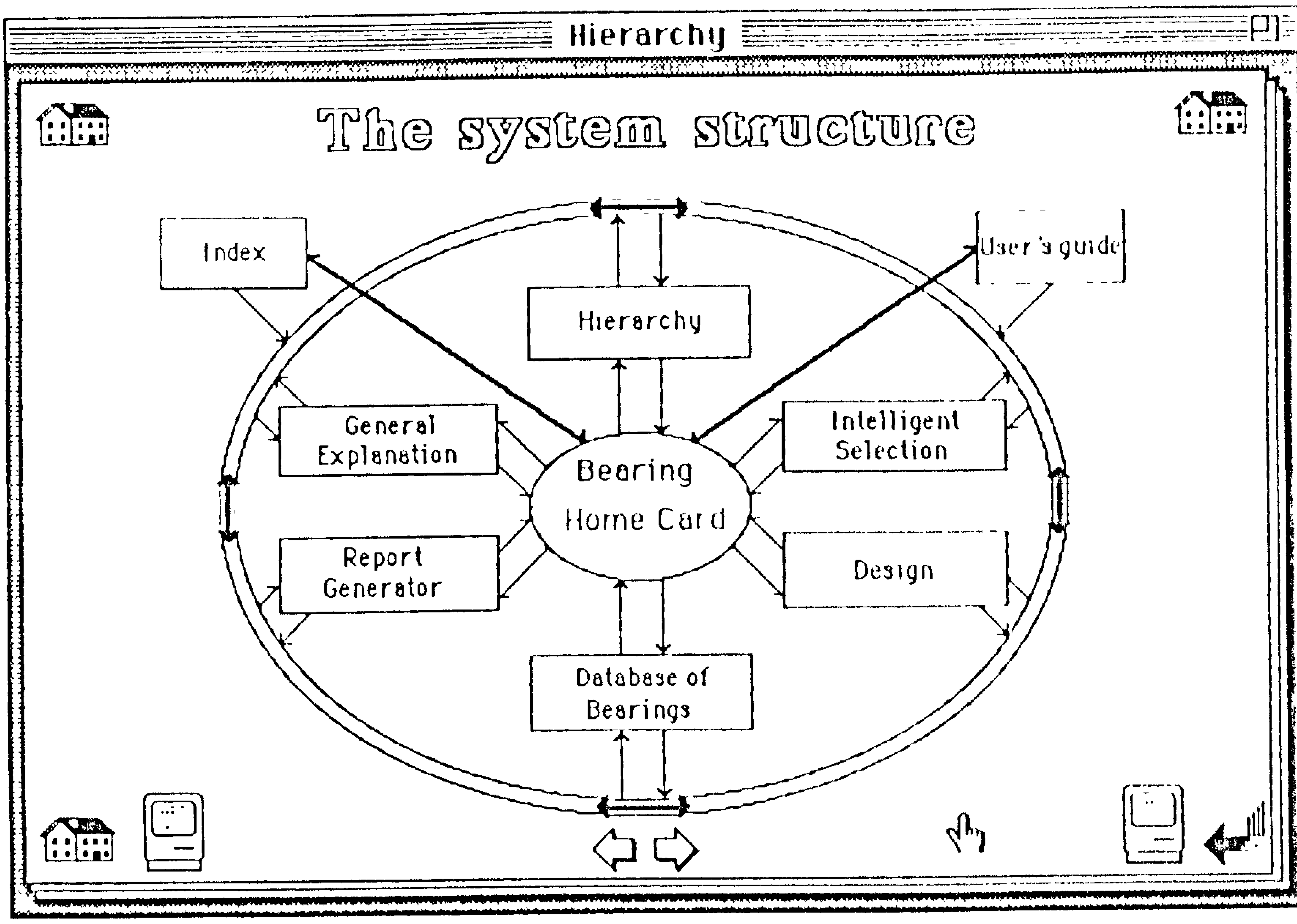
(a)


Hierarchy
Bearing Materials Tree
Common bearing materials
Body
Bearing bush
Shaft
Thrust plate
Bronze
Lead bronze
Brass
Graphite*
Mild steel
Mild steel
Nitrided steel
Low alloy steel
Sprayed materials on shaft
Stainless steel*
High chromium tool steel
Mild steel
Stainless steel*
Mild steel
Cast iron
Sprayed materials
Sprayed ceramics
* Materials primarily recommended for gas film bearings
Factors which affect material selection:
(1) High bearing pressure
(2) Material stability
(3) Corrosion resistance
(4) Thermal expansion and conductivity

(b)


Hierarchy
Liquid film bearings
Machine tools
Metrology equipment
Others
Grinding machine
Lathe
Boring machine
Rotary table
Roundness meter
Video
Radio telescope
HD driver
Gas film bearings
Machine tools
Instruments
Others
Lathe
Grinding machine
Boring machine
Driller
Gyroscope
Nuclear reactor
Medical equipment
Laser printer
Wheelhead spindle
Workhead spindle
Roundness meter
Flow meter
Dental drill
Orthopaedic cutting tool

(c)



(d)

Figure 6.14 Hierarchy trees in the hierarchy module

6.3.3 The bearing database module

Figure 6.15, shows the menu card of the bearing databases module. A system user can enter each bearing database by clicking the database title on the menu card or using the module pull-down menu. In order to retrieve a database quickly and accurately, some databases such as 'Nomenclature', 'Terms and concepts' and 'Bearing parameters' were developed using symbolic processing programs written in HyperTalk. As shown in Figure 6.16, for example, when a user clicks the retrieval icon at the bottom left of the 'Terms and concepts' database card, the module shows a dialogue window to ask the user to input the term or concept required. After input, the user can click the 'OK' button and the module retrieves the required information. The retrieval search is fast and the user is automatically guided to the information in the database. If the required information is not included in the database, the module will give a warning notice to the user. The following is a retrieval program associated with the 'Terms and concepts'

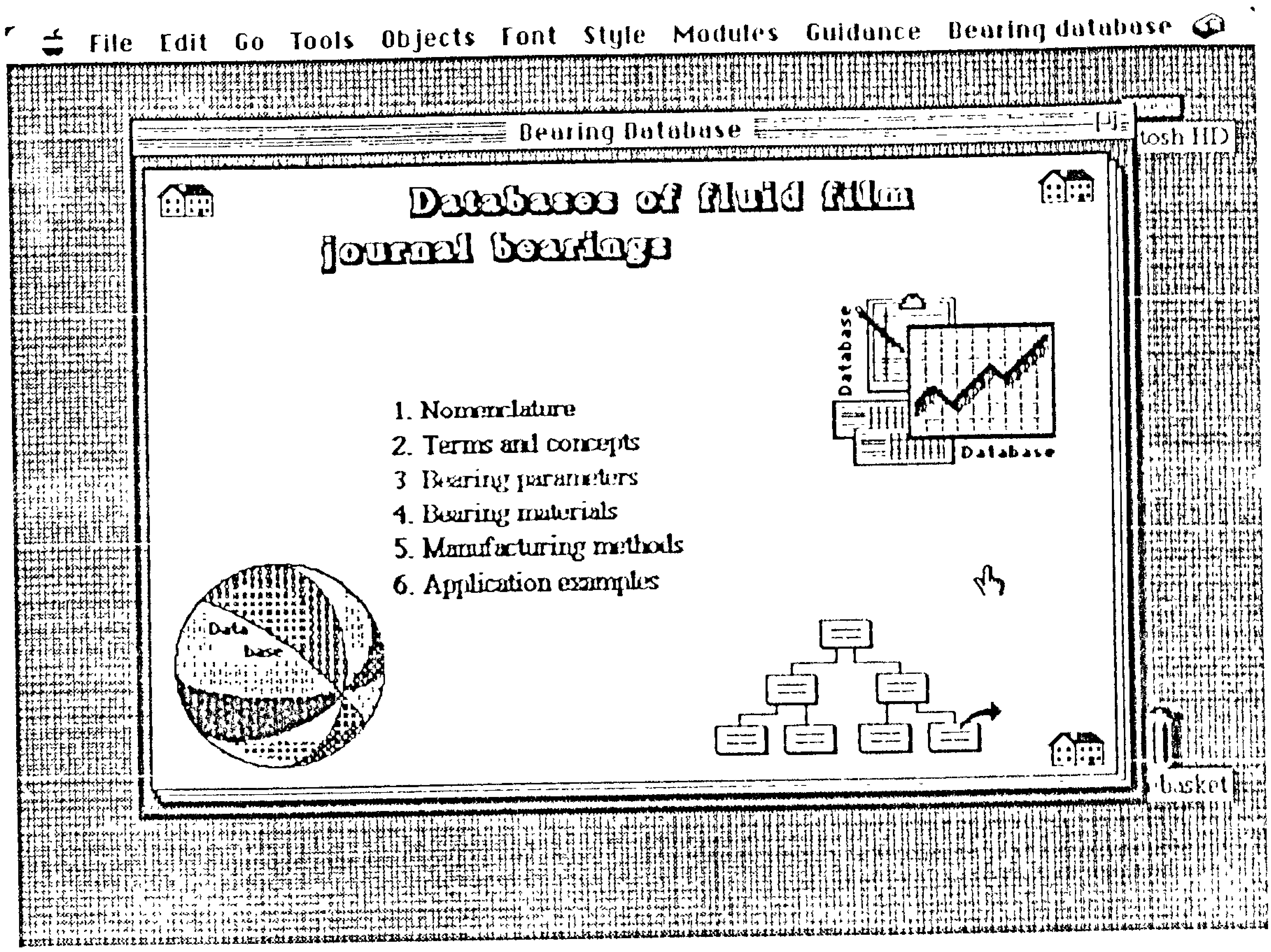
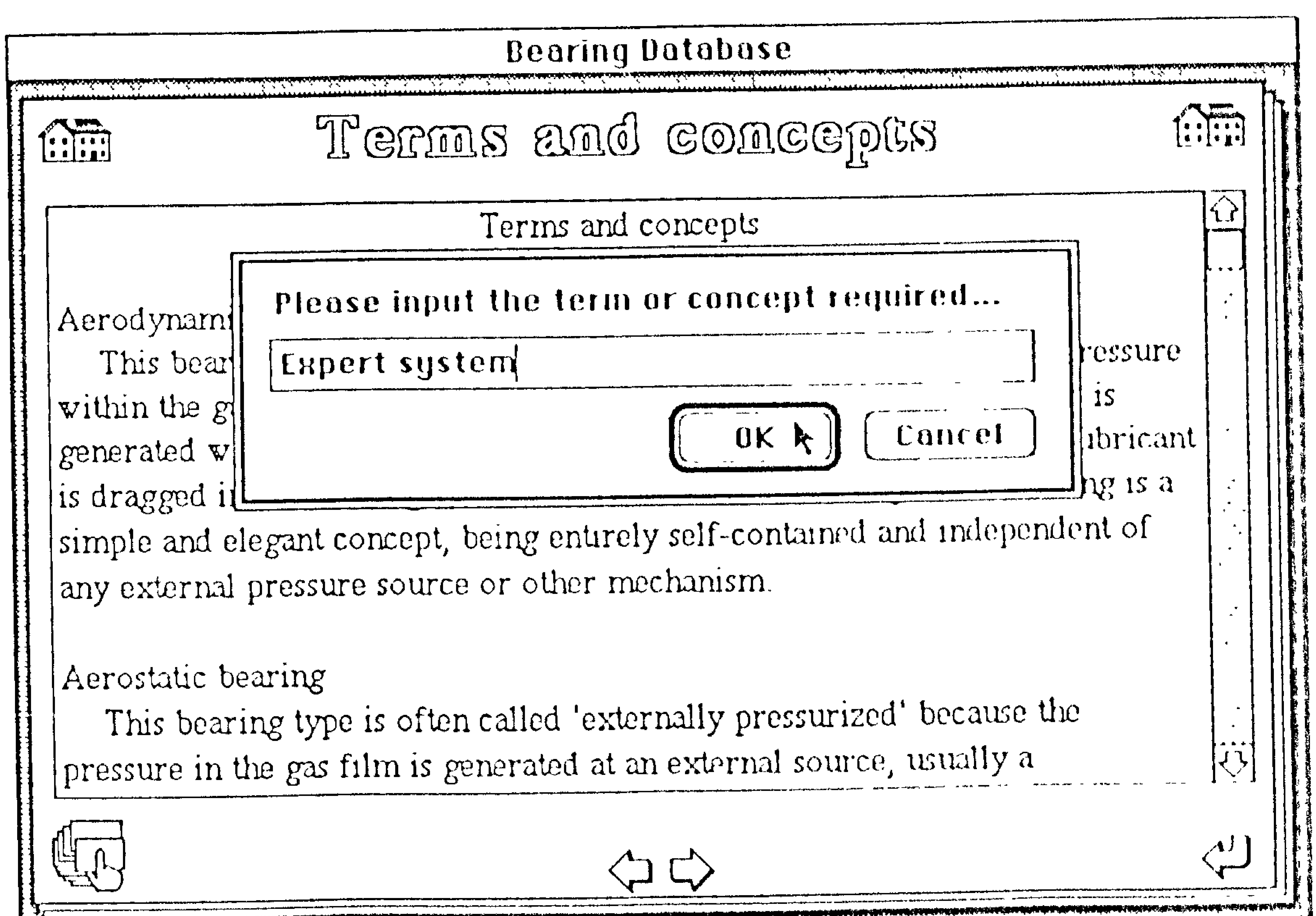
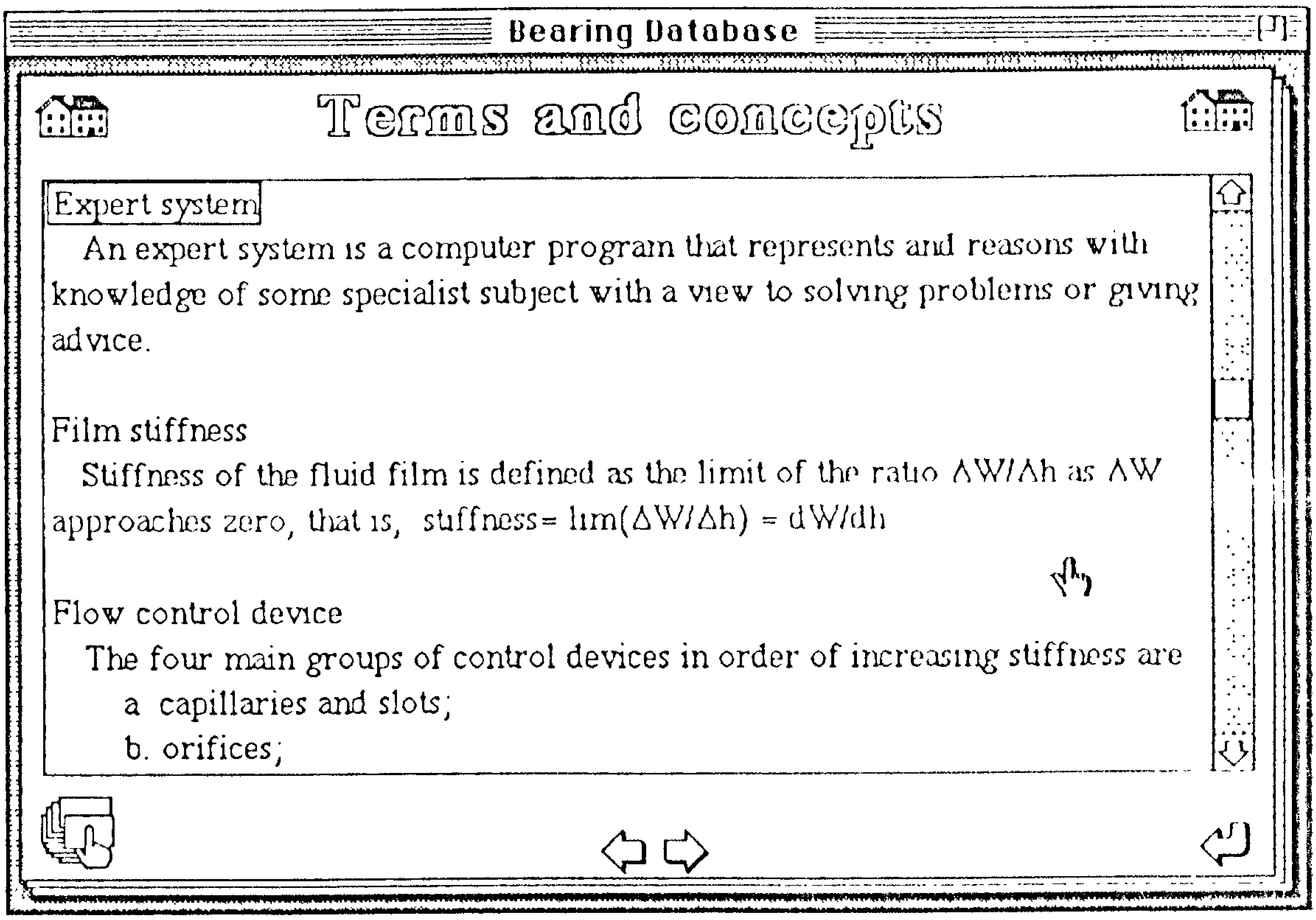


Figure 6.15 The menu card of the bearing database module



(a)



(b)

Figure 6.16 An example of the 'Terms and concepts' database

database, written in HyperTalk to allow symbolic processing:

```
On MouseUp
  ask "Please input the term or concept to be found."
  if it is empty then
    play "boing"
    answer "Your input should not be empty!" with "Cancel" or "Input
           again"
    if it is "Input again" then
      get the location of button search
      click at it
    end if
    if it is "Cancel" then
      go to card id 4253
    end if
  else
    find string it in card field container
    if it is not in card field container then
      put it into hold
```

```
        answer "The term is not in the system!" with "Define it"
              or "Cancel"
        if it is "Cancel" then go to card id 2842
        if it is "Define it" then
          put hold after last line of card field container
          find whole hold in card field containers
        end if
      end if
  end if
End MouseUp
```

6.3.4 The report generator module

With the report generator module, a system user can print various reports on a bearing design procedure as shown on the module menu card in Figure 6.17. The user can click the highlighted titles on the menu card and the module will print the corresponding

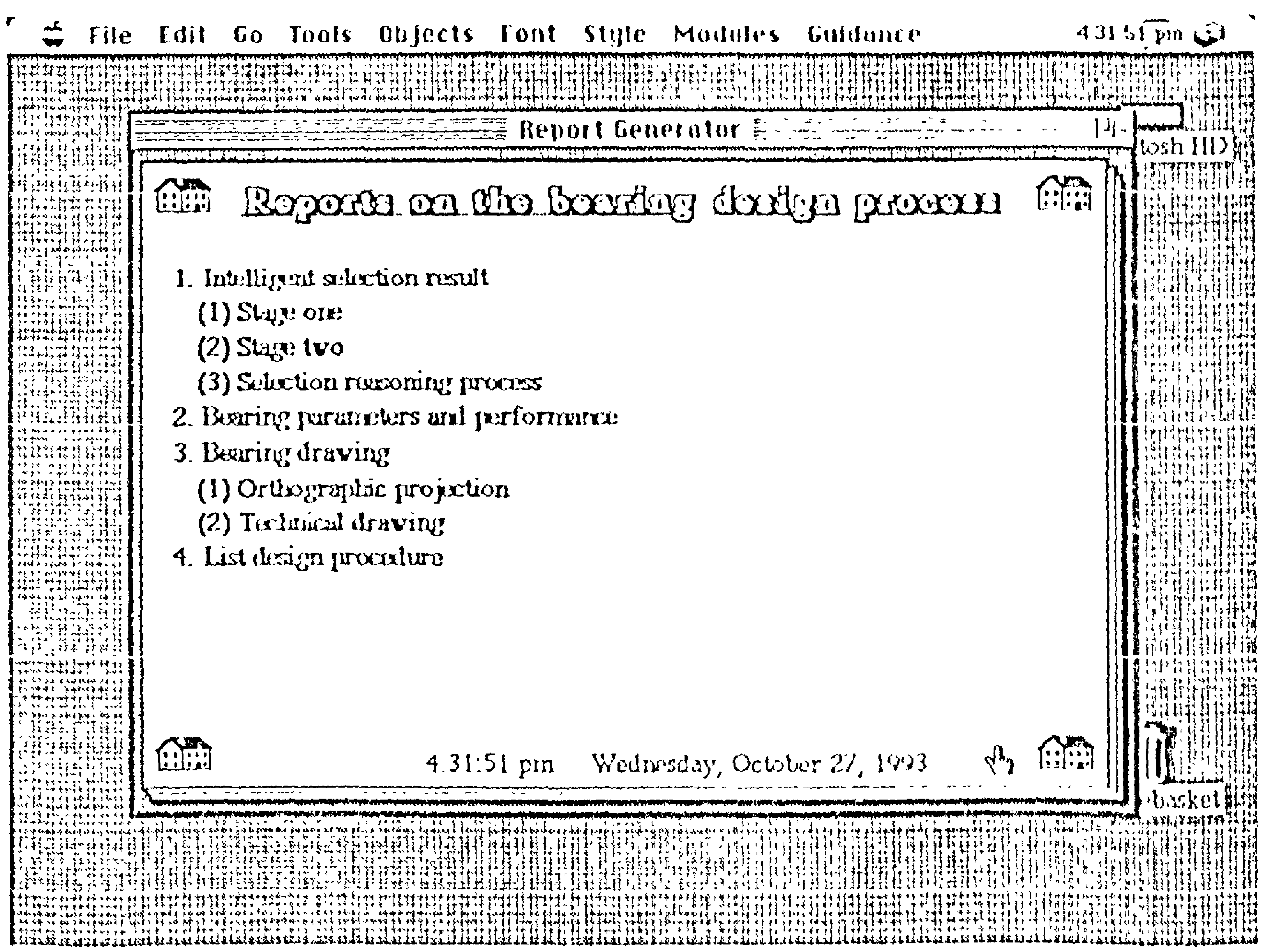


Figure 6.17 The menu card of report generator module

report. The report files are transferred to the module from other modules by using the 'file' statements of HyperTalk[85]. The user can also print reports within any other module of the system by using the module 'Printer' icons or the printing facilities listed in the system pull-down menu 'File'.

Chapter 7 Auxiliary modules and XCMD's programming

7.1 Introduction

Associative linkage is the distinguishing characteristic of a hypermedia-based system. However, the ability to create linkages, if not exercised well, can lead to the following problems[86].

- Getting lost in 'Hyperspace', i.e. the tendency for the user to lose the sense of location and direction during use of a hypermedia-based system.
- Cognitive overhead, i.e. the difficulty of learning how to create, name, and keep track of the links within a hypermedia-based system for a developer.

In this design support system, two auxiliary modules were developed indicating the index and help modules. These auxiliary modules are used to cope with the above-mentioned problems. The Help module is also used as a user guide to assist users to use the system. As described in Chapter 5, XCMD programming can be employed as an auxiliary measure to enhance the capability of the HyperCard environment for complex computing and to allow the incorporation of special functions.

7.2 The help module

A system user can easily access the help module when browsing the system or when in any other modules by using the system 'Guidance' pull-down menu, the 'help' icon on the 'Home' card, or directly through the keyboard (Commandkey + ?). Figure 7.1, shows the menu card of the help module. The user can click the highlighted titles on the card to obtain guidance on how to use the system and the theoretical basis for the system development. The user can also click 'Introduction', 'Search', and 'Printer' icons on the card to get the introduction about HyperCard, to retrieve and print the instructional information within the module. The 'You are here' icon has a tracing and mapping function. When the user clicks it, the module shows the user as many as 42 cards that were previously displayed. A user can also access the mapping function by using the 'Guidance' pull-down menu. Figure 7.2 shows a tracing sequence of the use

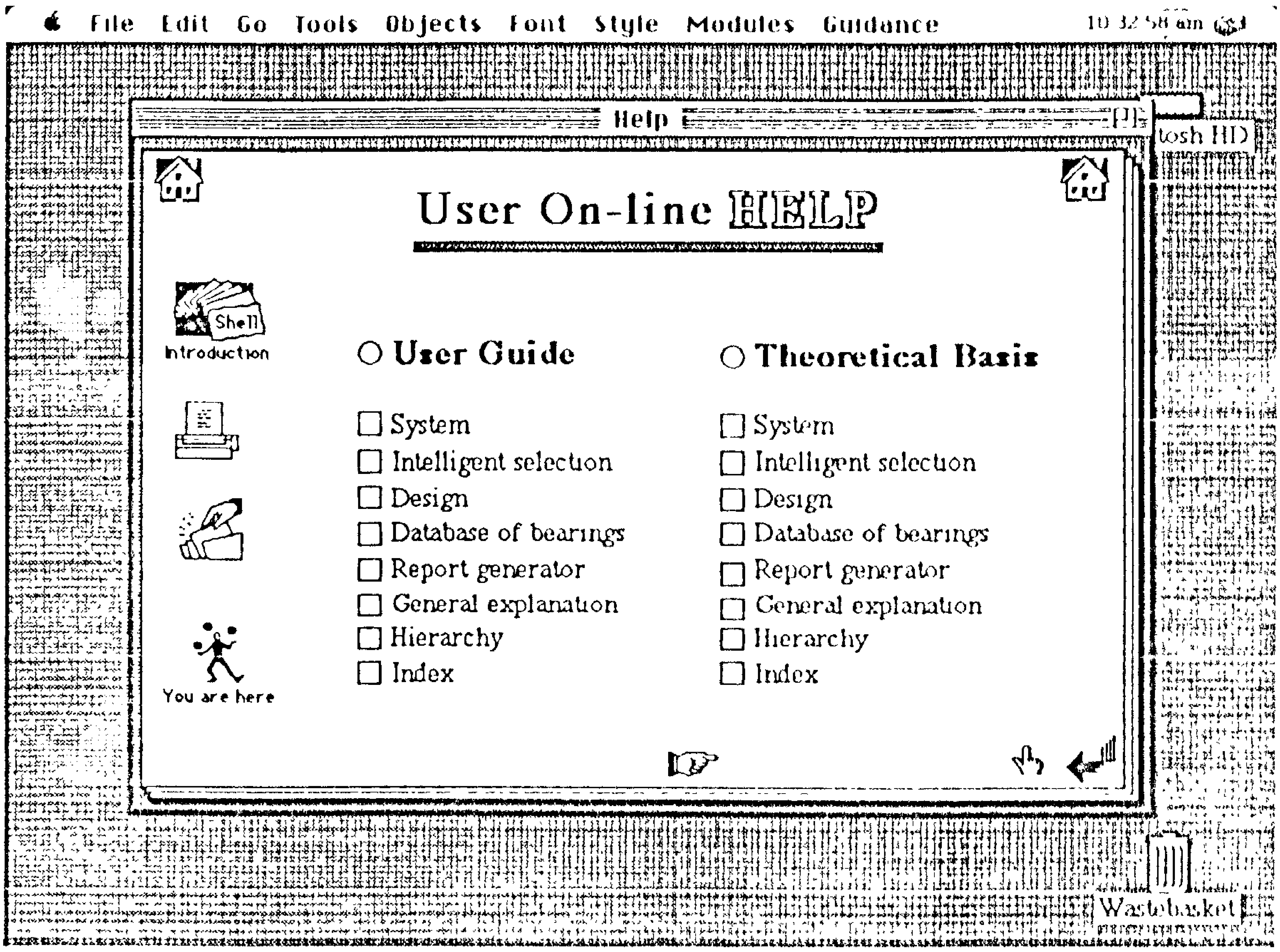


Figure 7.1 The menu card of the help module

of the system. After browsing the module and obtaining required information, a return to an original position is achieved by simply clicking the 'return' button on each module card. This on-line jumping ability is realised by using an elegant symbolic processing program written in HyperTalk. For this reason the module is more appropriately called the user on-line help module. The on-line help combined with the tracing and mapping function helps to overcome the problem of getting lost in 'Hyperspace'. Figure 7.3, illustrates the working principle of on-line jumping within the system.

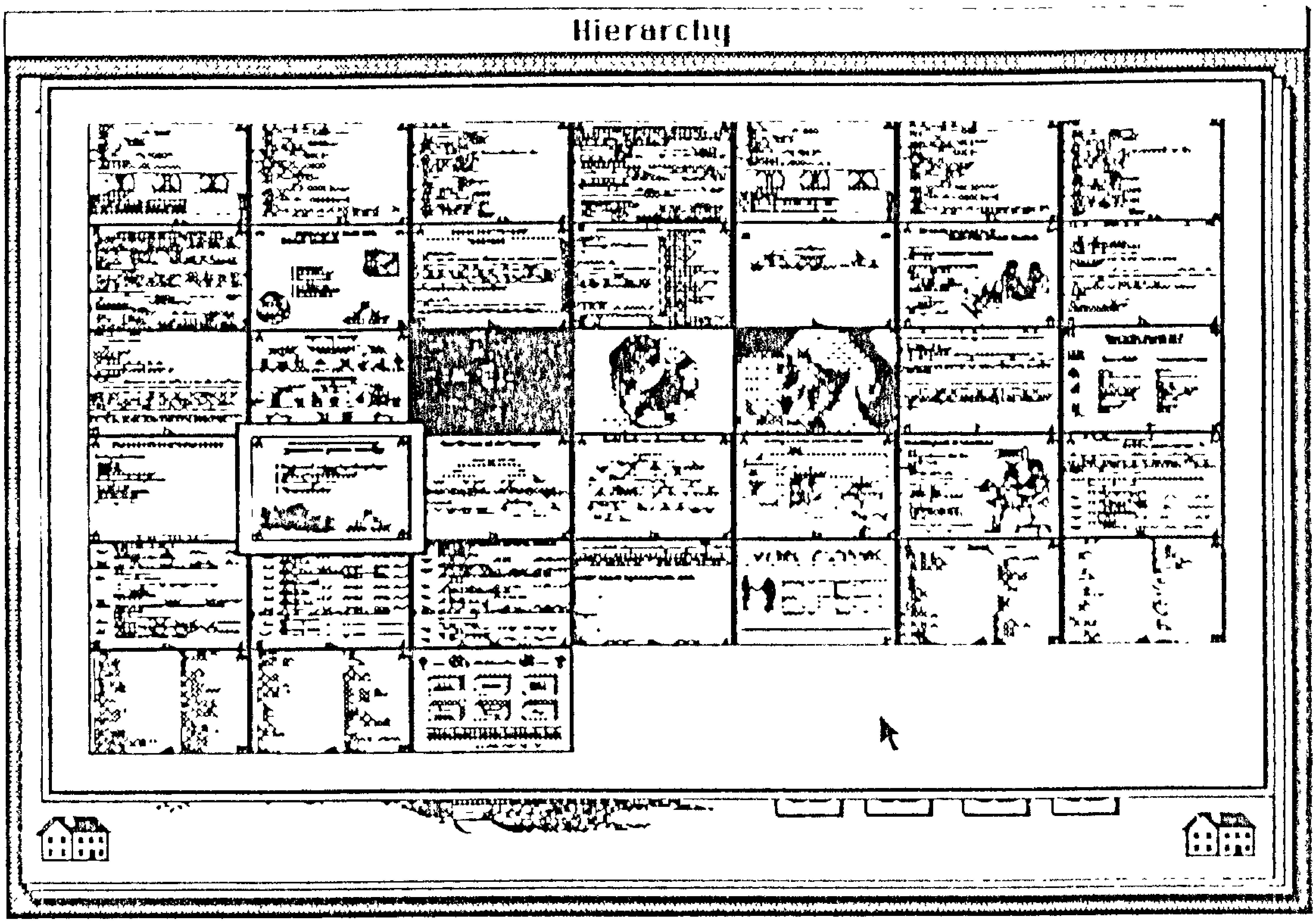


Figure 7.2 A trace of sequences followed by a user

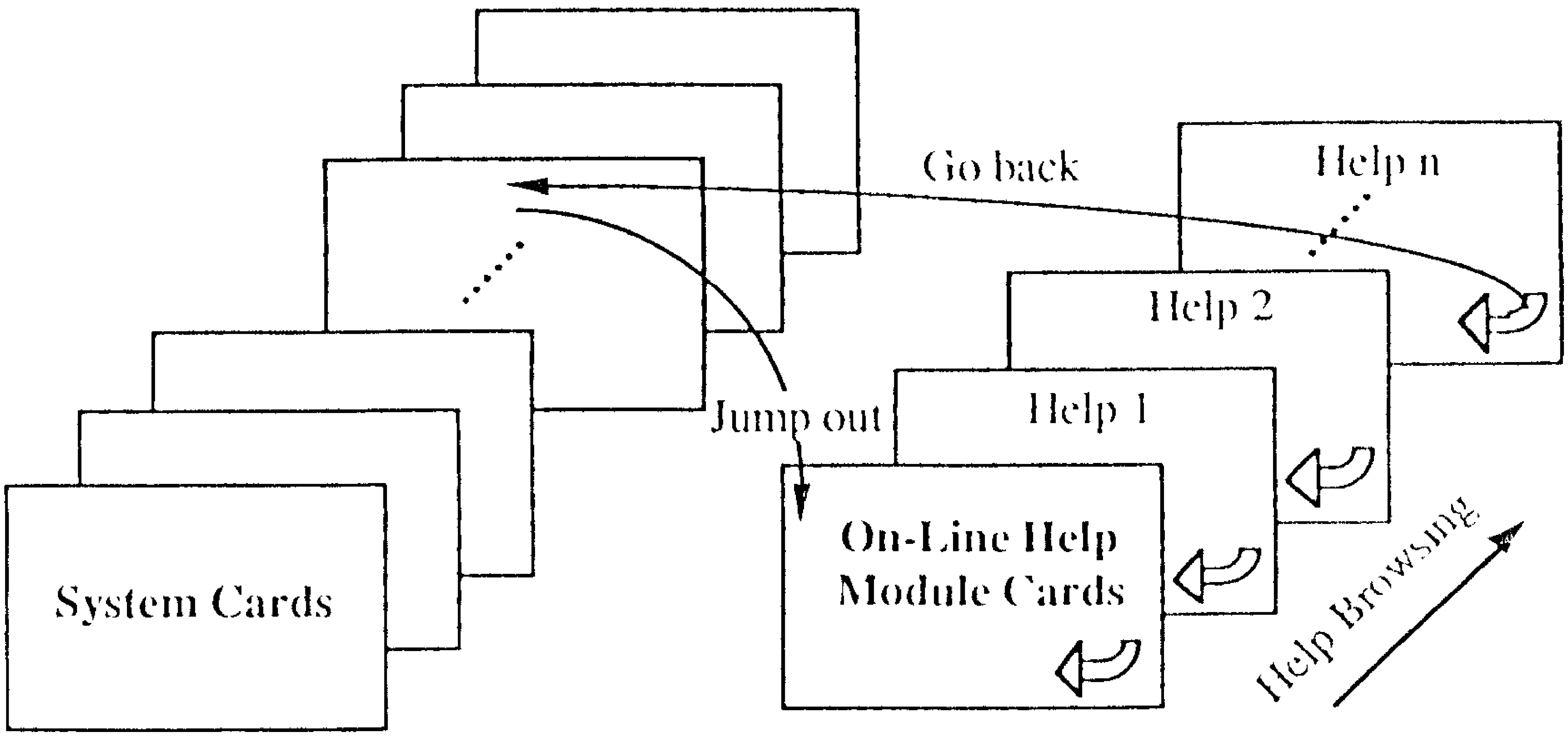


Figure 7.3 The principle of on-line jumping within the system

7.3 The index module

The index module is developed using hypermedia techniques. The function of the module is similar to that of a book index. However, the module structure is different from the structure of a book in two respects:

- Using a symbolic processing program, the module index search can be carried out automatically or the search can be done manually. As shown in Figure 7.4, the module can automatically guide the user to the indexed word on a card.
- All of the index words or terms on the module cards are highlighted and linked with their related corresponding information in other modules. The user can click any indexed word or term to be guided to the associated information or knowledge.

The linkage between each index term and its related information is created by using the hypermedia node-link technique and operates in an associative way.

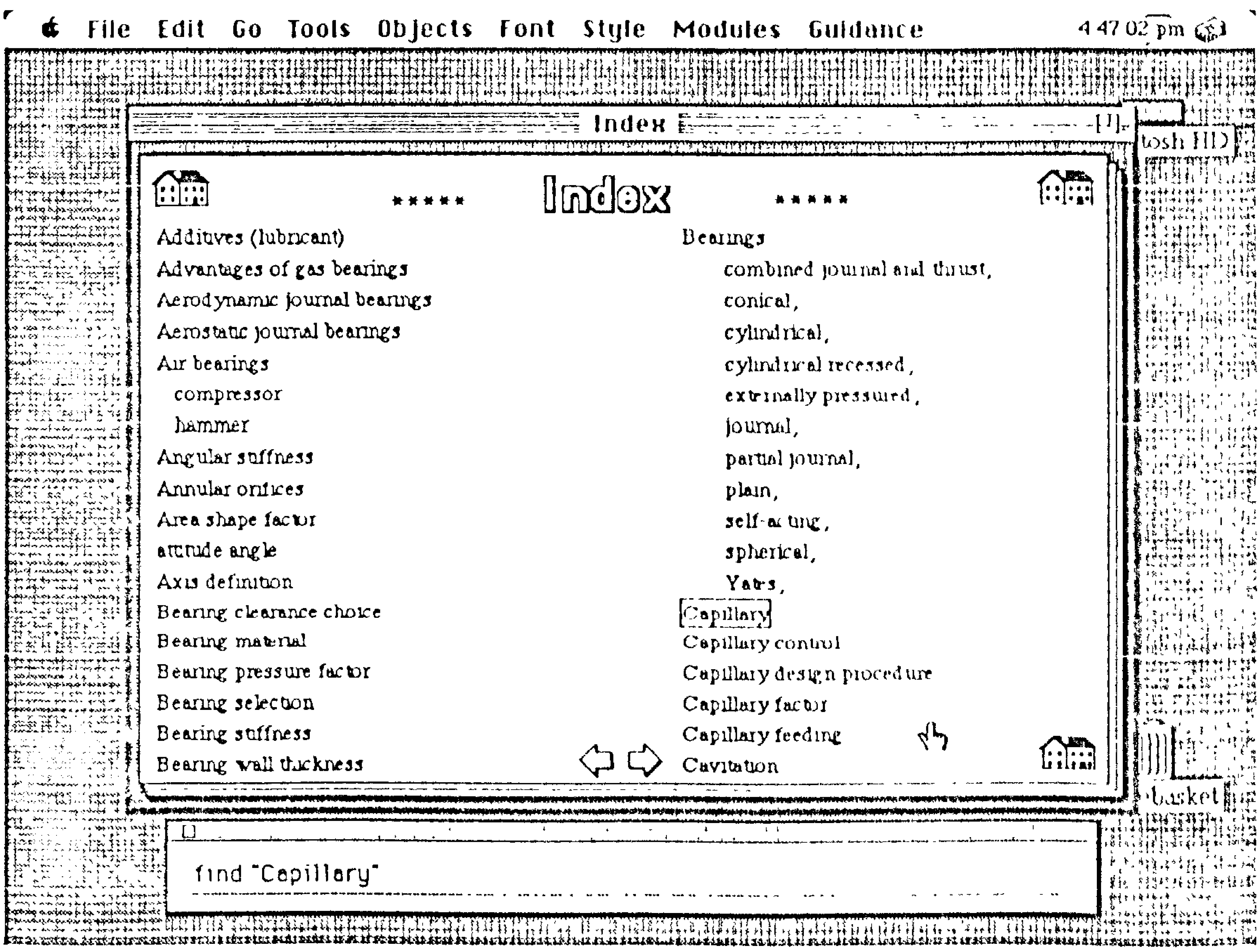


Figure 7.4 The index module card

7.4 XCMD's programming

An XCMD can be written in Pascal, C, or Assembly language and, after being processed through a compiler or assembler, attached to a HyperCard stack as a resource. In the HyperTalk programming environment, an XCMD is taken as a command statement or a subroutine program that HyperTalk scripts can call in or jump to. Therefore, XCMD programming is a customised extension of HyperCard which can be employed for a special purposes. XCMD programs can greatly enhance HyperCard in operational speed and complex performance[87].

XCMD programs written in Macintosh Workshop Pascal [87][88] were developed and associated with each system module. The XCMD programs are used to append a single menu to the end of a HyperCard menu bar or to remove a menu from a HyperCard menu bar. The XCMD programs are called AddMenu and ClearMenu. The system uses the AddMenu and ClearMenu XCMDs in developing the pull-down menus in the system and allow the user to use the system much more flexibly.

(a) XCMD AddMenu

The XCMD AddMenu requires three parameters:

- Parameter 1: The name that will appear in the menu bar.
- Parameter 2: A unique number greater than 200 that will represent this customised menu.
- Parameter 3: A double-quoted, semicolon-separated list of menu items that are to appear in the menu.

AddMenu can support the following meta functions:

- Symbol ! followed by a character, marks the menu item with that character.
- Symbol < followed by B, I, U, O, S sets the character style of that menu item. B stands for bold; I stands for italic; U stands for underline; O stands for outline; S stands for shadow.
- Symbol / followed by a character, creates a keyboard equivalent.
- Symbol (disables an item.

- Symbol (- inserts a grey out line.

The following is a HyperTalk program using the XCMD AddMenu in the system 'Home' stack, which creates the system customised pull-down menus 'Modules' and 'Guidance' as shown in Figure 7.5.

```
on openStack
  AddMenu "Modules",600,"Bearing database;Design;General
        explanation;Hierarchy;Intelligent selection;Report
        generator"
  AddMenu "Guidance",609,"Help/?;Index/5;Map/6"
end openStack

on doMenu var
  if var is in "Bearing database,Design,General explanation,
             Hierarchy,Index,Intelligent selection,help,Report
             generator"
  then go to stack var
  else if var is "Map" then
    domenu "recent"
  else pass doMenu
end doMenu
```

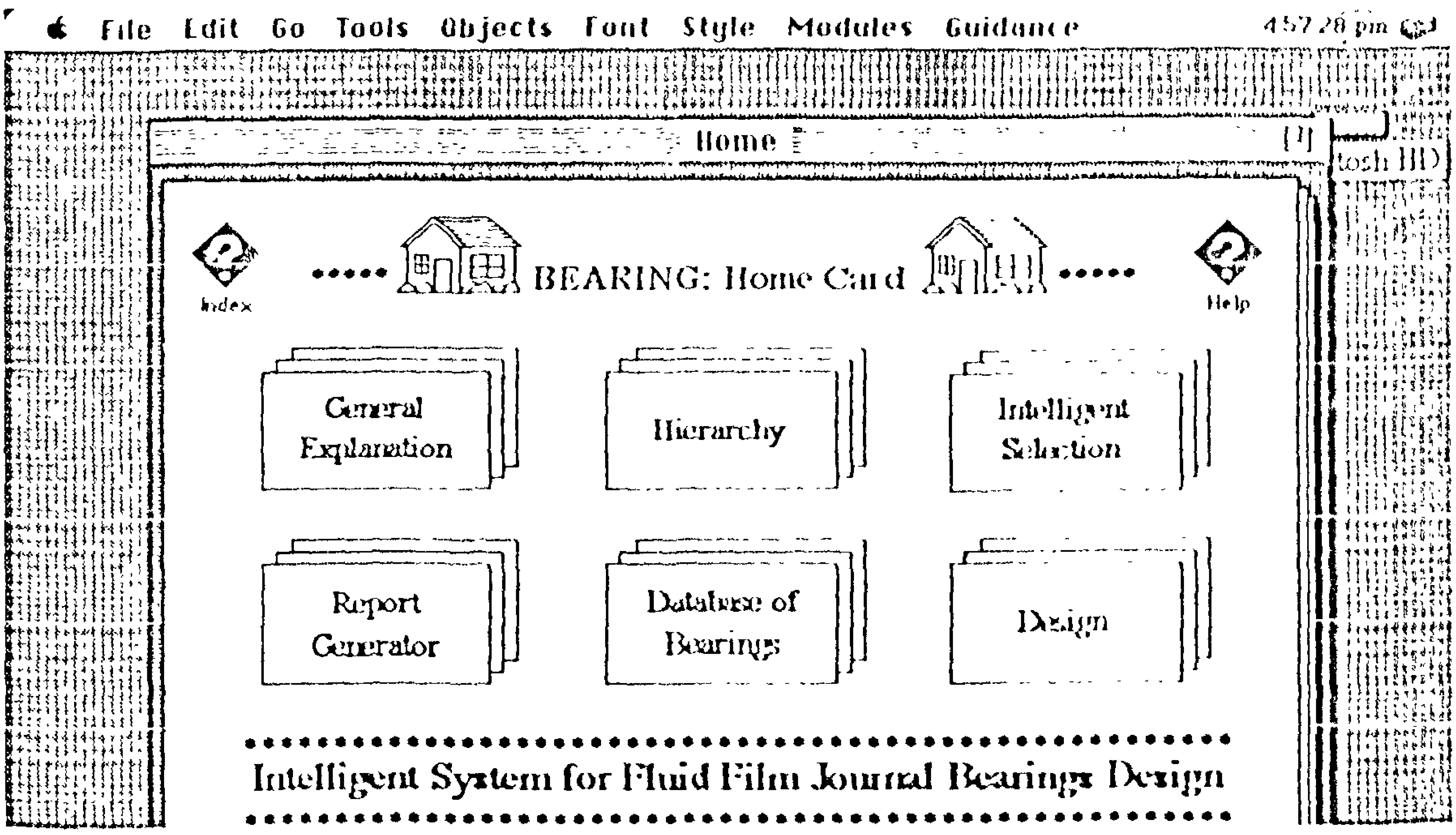


Figure 7.5 An example menu modified using XCMD AddMenu

The source program for XCMD AddMenu written in Macintosh Workshop Pascal is shown in Appendix I.

(b) XCMD ClearMenu

The XCMD ClearMenu employs the menu ID number of the menu to be removed. The menu to be removed must be specified by its menu ID number. The following is a HyperTalk program using XCMD ClearMenu in the module 'General Explanation', which removes the menu 'General Explanation' from the module built in pull down menus as the module closes.

```
on OpenStack
  AddMenu "General Explanation", 400, "Introduction; Theoretical
          basis; Design and manufacturing; Applications;
          Development trends"
end OpenStack

on doMenu var
  if var is in "Introduction; Theoretical basis; Applications;
               Development trends"
  then go card var
  else if var is "Design and manufacturing" then
    go to card var
  else pass doMenu
end doMenu

on CloseStack
  ClearMenu 400
end CloseStack
```

The source program for XCMD ClearMenu written in Macintosh Workshop Pascal [87][88] is shown in Appendix II.

Chapter 8 Human-computer interaction issues in system development

8.1 Introduction

Human-computer interaction (HCI) is the study of the interaction between people and computer systems. HCI is principally concerned with understanding how people and computer systems interactively carry out tasks, and how such interactive systems are designed[89]. HCI issues are receiving more and more attention in software system development. The principles of HCI are important in establishing user satisfaction with system aspects such as the system interface, user-friendliness, performance speed, and learning time. In this chapter, some HCI issues arising from the system development are discussed. The issues mainly focus on aspects of the system interface design, interaction, and the system evaluation.

8.2 Design principles of the system user interface

Design of the system user interface should be considered from a number of different perspectives which include the functional, the aesthetic, and the structural perspectives. Each of the perspectives interacts to affect the quality of the overall user interface design. The use of Apple Macintosh as the system platform is one of the directions towards achieving user-friendliness. Macintosh computers were one of the first to employ a 'WIMP' user interface where the user has multiple windows, iconic, and menu object representation and a pointing device. Since the commencement of the project, WIMP style interfaces have made important strides towards becoming the most important class of interfaces for future systems as predicted[90]. For the design support system, however, the appropriateness of its user interface heavily depends on the design task, the system users, and the environment for which the standard WIMP user interface cannot adequately cope. The following discussion concerns some principles used in designing the system interface.

(a) Metaphors

The system was developed for mechanical engineers of whom some may have little experience of using computer systems or reluctant to learn about new systems. However, engineers can be expected to have some experience of achieving their engineering objectives. To take advantage of this prior experience, the system was designed using metaphors for system operation that correspond to the engineering and everyday world that engineers are comfortable with. For example, the system uses graphic icons to represent specific bearing configurations. The icon graphics come from the engineers' working environment. The icons have the advantages of faster processing and recall of visual images. The advantages are associated with ease of learning, recall and recognition, and less interference with cognitive processes of using the system.

In general, a system user also appreciates visual effects, such as zoom in or out and animation, that show a requested action being carried out. Visual effects can support the metaphor. For example, using visual effects such as animation for demonstrating hydrostatic principles and 'zoom open', 'dissolve' and 'wipe left/right' when browsing the system from one card or one stack to another, provides a metaphorical effect and enables users to achieve a better understanding of the system and its inbuilt knowledge.

(b) Direct manipulation

From the psychological point of view, system users expect their physical actions to have physical results[91]. For example, when an iconic button is pressed, users like to see the corresponding process of the button being pressed down to be illustrated on the screen; when the optimisation button is pressed, the users like to see the iterative computing process explicitly illustrated if the speed makes this possible. Combination of a physical activity and feedback reinforces the sense of action.

The system users want topics of interest to be highlighted. Users want to see that required functions are available at any given moment. Users want clues that tell them that a particular command is being carried out, or, if it cannot be carried out, they want to know why not and what they can do instead. Through direct manipulation of interface elements, for example, the system users should be provided with a feeling of confidence that they are in charge of rather than being driven by the system.

(c) Consistency

There should always be one coherent way for the user to implement actions because users want to rely on familiar and straightforward ways to get things done. For example, icons having the same function should be consistent in appearance. The style of the system screen should be consistent otherwise the displays will be confusing and distracting. In most cases, consistency should be valued above idiosyncratic cleverness[92]. An application should be both consistent within itself and consistent with other applications.

(d) Aesthetic integrity

In traditional software development, the visual appearance of the screen was of less concern than the software operation. The aesthetic integrity of a software system becomes more important in the development of software industrialisation and commercialisation. The following are some rules important for the aesthetic integrity of the system design which have become apparent during the course of the project.

- Avoid cramming too much information onto a single screen display. The screen display should be concise and ease to follow.
- Avoid visually confusing or unattractive displays. For example, the golden section principle is recommended used for the system screen layout. Abnormal proportions for the width/length ratio of a screen display should be avoided.
- Different 'things' should look different in the system screen. For example, the difference between text and text icons should be identifiable.
- Different fonts have different effects on the overall appearance of the interface, especially for the presentation of text-based information. The appropriate selection of font styles and size helps to avoid confusion and achieve a pleasing result.

8.3 Design of the interface elements

(a) Icons

The system has a variety of icons to represent actions and objects. All of these icons can be invoked or manipulated by a user. Figure 8.1, shows some typical icons used in the system. There are mainly two types of icon. One is the pictorial icon to represent engineering objects. The other is the text-based icon to convey abstract concepts. Some pictorial icons with text titles are used for situations where pictorial icons used in isolation from text may lead to misunderstanding.

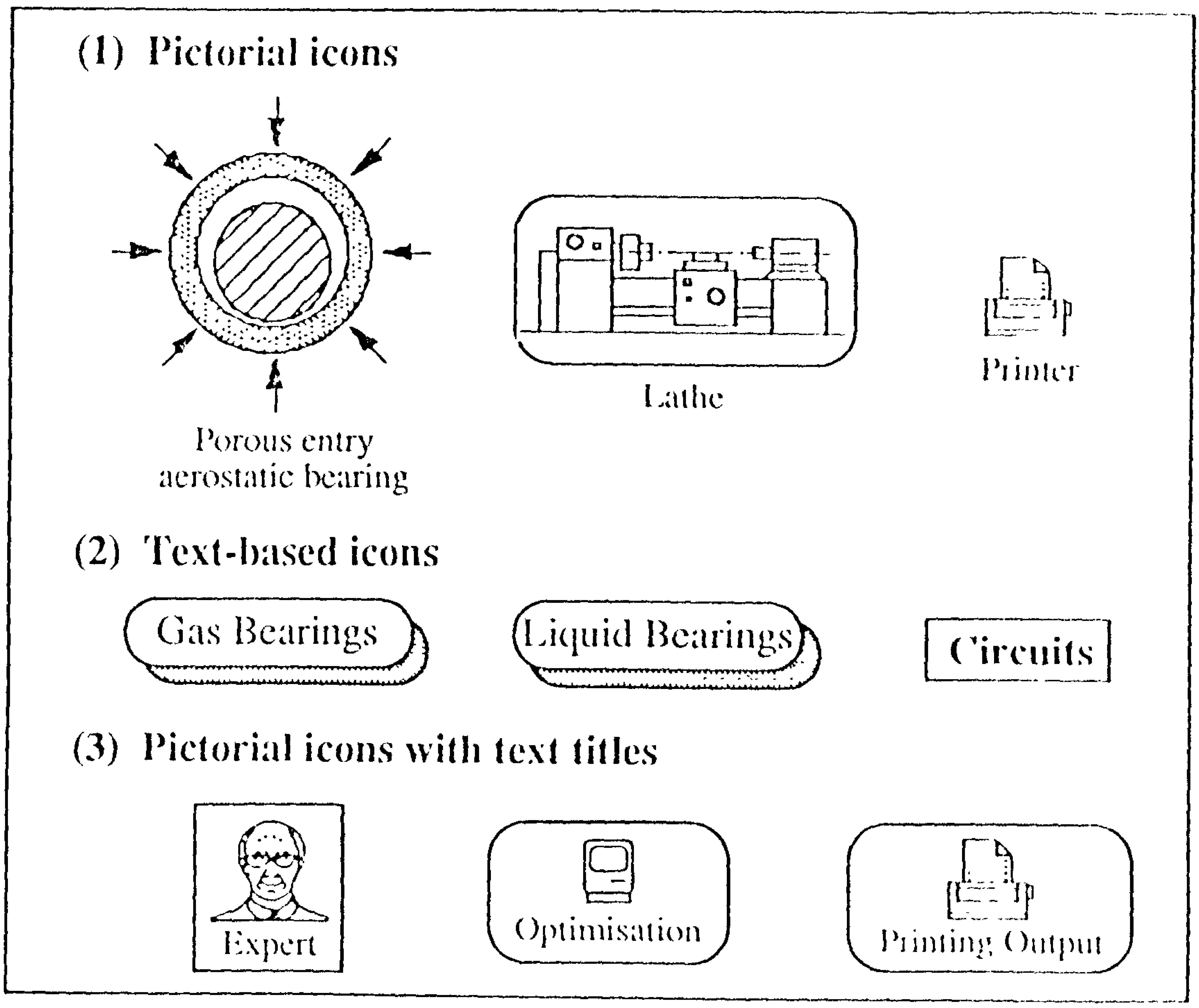


Figure 8.1 Typical icons used in the system

Experiments illustrate that using icons as an interface element has the following advantages[93]:

- Provision of a concise metaphor,
- More rapid processing,

- Compact display space,
- Object orientation, and
- Ease of learning, recall and recognition.

The use of icons may also have disadvantages which arise from difficulties in implementation. Making icons easy to understand, avoiding misleading analogies, and carefully designing iconic interactions are essential rules for making the best use of icons.

(b) Pull-down menu

As shown in Figure 5.2, the system has pull-down menus which are programmed in Macintosh Pascal and linked with the system by XCMDs. Figure 8.2, shows the

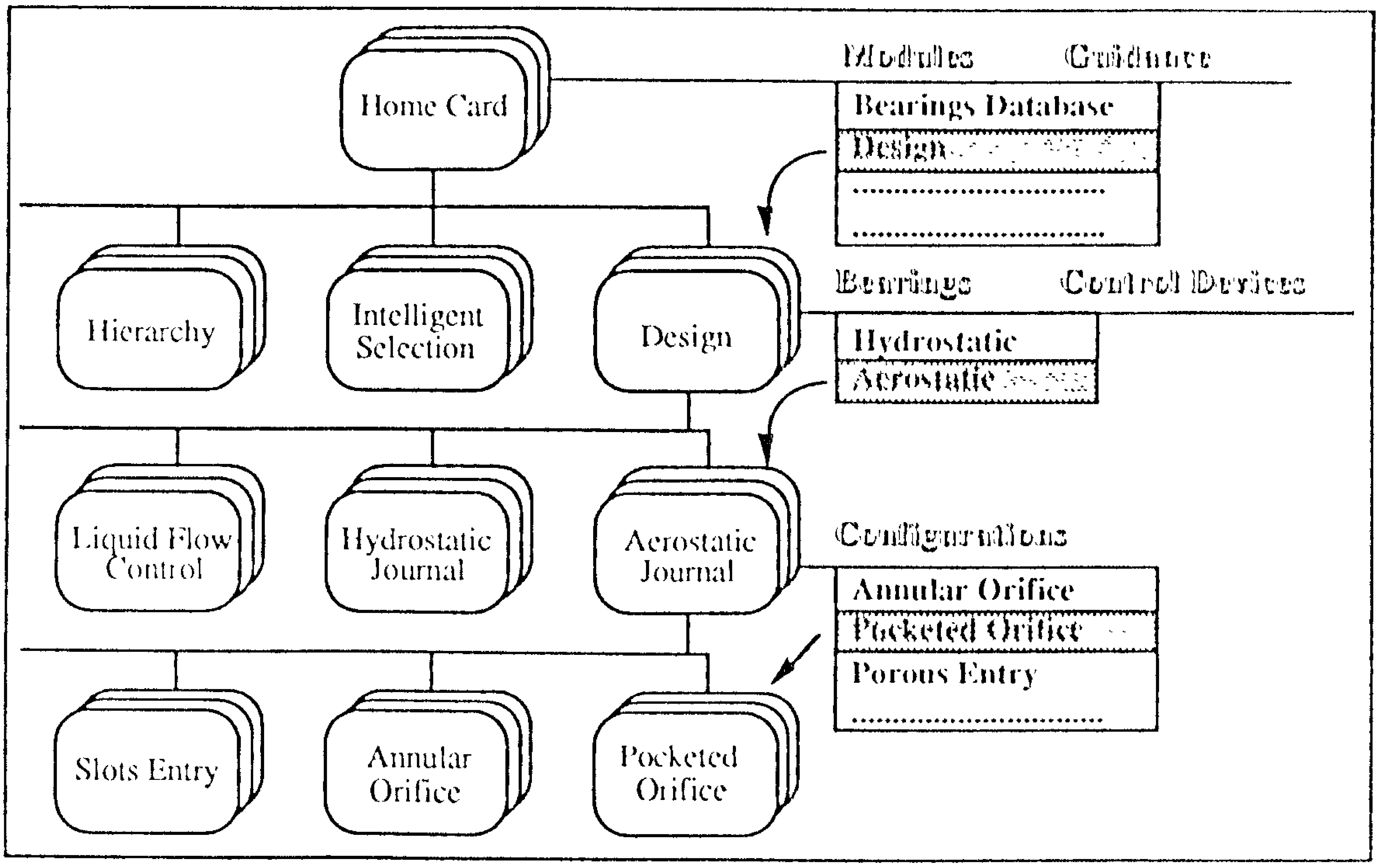


Figure 8.2 The working principle of the system built-in menus

principle of the menus. The system has constantly available menus of 'Modules' and 'Guidance' which a user may access in any part of the system. In different modules or parts, however, the system also has module-specific menus which are automatically added or removed as the modules or parts are opened or closed. The criteria for the design of the system pull-down menus are as follows:

- To enable a user to access any module or part of a module through the menus regardless of which part of the system the user is working in.
- To enable a user to access guidance aids at any time. The aids include index search, tracing and mapping, and on-line help.

(c) Screen design

Using HyperCard as the system development environment provides a 'Card' style screen which formulates the screen layout to some extent. However, there is still considerable space for a developer to customise the system layout. The following discussion is concerned with the major considerations involved in the system card design. Figure 8.3 gives a graphical illustration of some concepts referred to in the discussion.

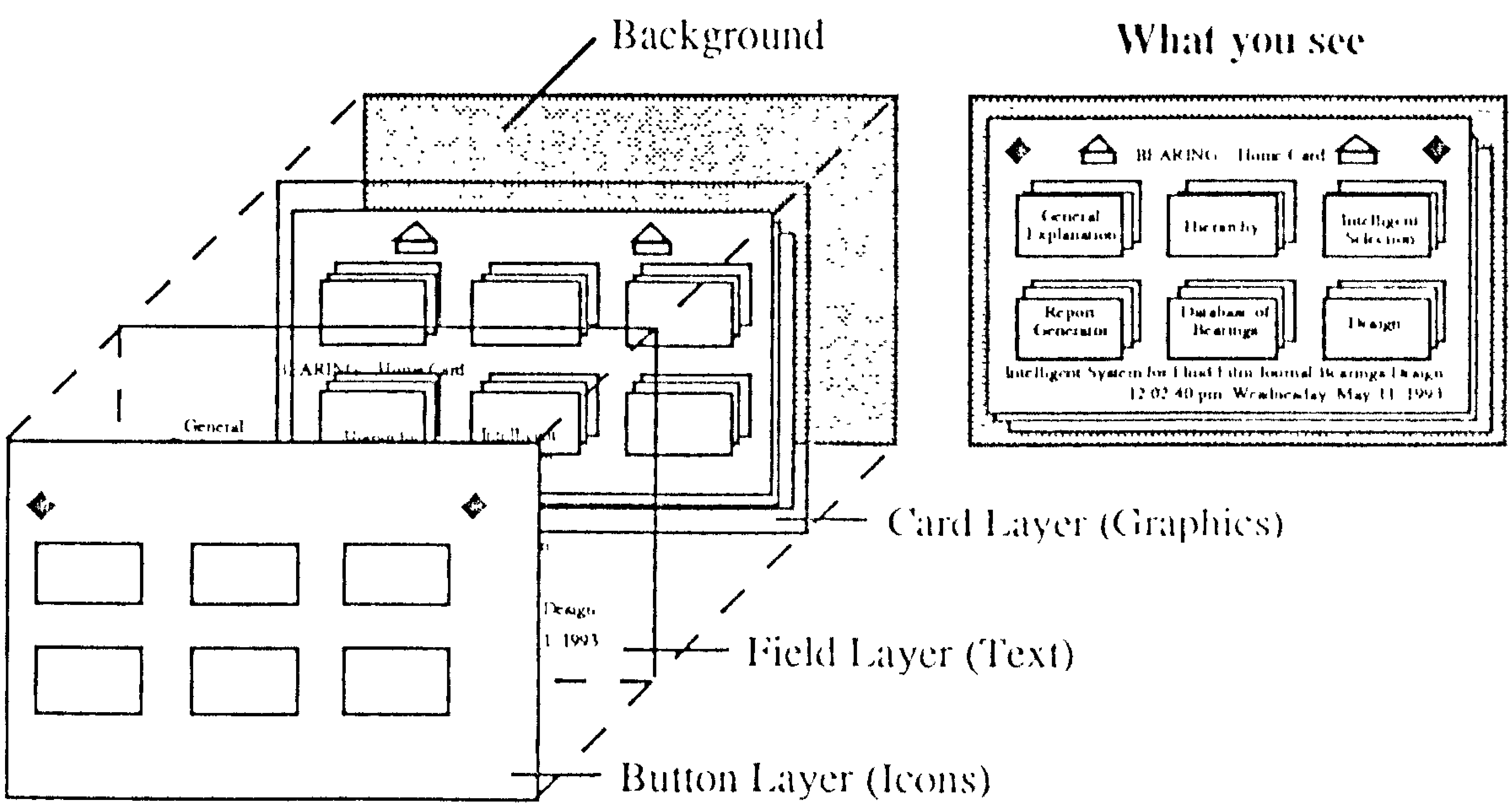


Figure 8.3 A graphical illustration of some concepts

- Background format: The information displayed on each system card is actually on a layer over the background. As shown in Figure 8.3, the visual effects of the system card can be performed by orchestrating the interaction of background and card layers. The underlying philosophy of the system background design is to make it appealing, intuitive and consistent, so that users are not distracted when they work through the information built into the system cards.

- Card size: The system uses a 'standard' 9 inch screen layout because some Macintosh models such as the Macintosh SE/30 and Macintosh Classic have 9 inch screens. Each card has a size of 9 inch maximum. The ratio of card width to length is chosen based on the golden section principle, i.e it is about 0.618 if possible
- Fields and buttons: The fields and buttons are two major objects in the HyperCard environment. Fields are mainly used to contain text. A field has five styles such as transparent, opaque, rectangular, shadowed and scrolling which can be freely chosen by the designer. Buttons are icons which perform actions. The action that a button carries out is entirely determined by the HyperTalk scripts assigned to the button. A button has seven styles including transparent, opaque, rectangular, shadowed, rounded rectangular, check box and radio button. A button also has other properties such as 'auto hilite' and 'graphical icon editing' which can be freely selected. The properties inherent with both fields and buttons are quite flexible in use. Their layout designs depend on the requirements of the whole screen layout.
- Text: The system mainly uses 'Times' font and '14 point' size for text-based information display. The text characters and space should be sufficiently large for good legibility. The system also uses highlighting such as underlining and flashing text to highlight headings and titles. However, overuse of flashing or blinking can be irritating to the user.

(d) Sound

The system integrates sound into the interface to give users additional information. The use of sound in the system is achieved by using HyperTalk programming. There are three ways that sound is used in the system.

- Getting attention: For example, when the system is undertaking a time consuming operation, the user may have turned away from the screen. The inbuilt sound or short music is a useful way to let the user know that the process is finished, or it needs attention. Sound or music is usually combined together with an indication on the screen such as a message.

- Alerts: The system uses sound with an alert box to warn users of critical operations and mistakes.
- Modes: The system has different modules and operation states. Some modules such as 'Report Generator' and 'Help' are introduced with a short burst of music to herald entry into the module.

Although sound can be used as an effective element in building the system user interface, it may also bring problems if overused. In a quiet working environment such as a laboratory or design office, the sound or music may be annoying. For this reason the system sound volume can be controlled by the user who can change the volume of sound, or turn the sound off.

Figure 8.4, illustrates two short programmes within the system written in HyperTalk in order to create sound and music.

```
if min(D1,D2)<mmm1 or max(D1,D2)>mmm2 then
   play "boing"
   answer "Calculated D(mm) is out the required range!" with "Continue" or "Stop"
   if it is "Stop" then
     answer "Change input: increase supply pressure Ps."
     exit repeat
   end if
end if

on openstack
   play "harpsichord" tempo 120 "ce e g c5 e g4 c5 e"
   global HelpExit
   push recent card
   pop card into it
   if "help" is not in it then put it into HelpExit
end openStack
```

Figure 8.4 Two HyperTalk programmes for making sound and music

8.4 Interaction aids

The user may directly manipulate icon/menu objects on the screen. By using a mouse, the user can point to objects, select objects with a click of the mouse button, and choose actions to apply to the selected objects. Direct physical control over the system environment puts the user in command and optimises the 'see-and-point' style of interface. However, a simple icon/menu driven interface is insufficient for the interaction required to undertake a complex design task.

As shown in Figure 8.5, the system incorporates user system interaction support. The support includes the on-line help from the help module and design guidance from the AI. The use of the help module improves the system learnability and self-explanatory capabilities. The help module was described in detail in Chapter 7.

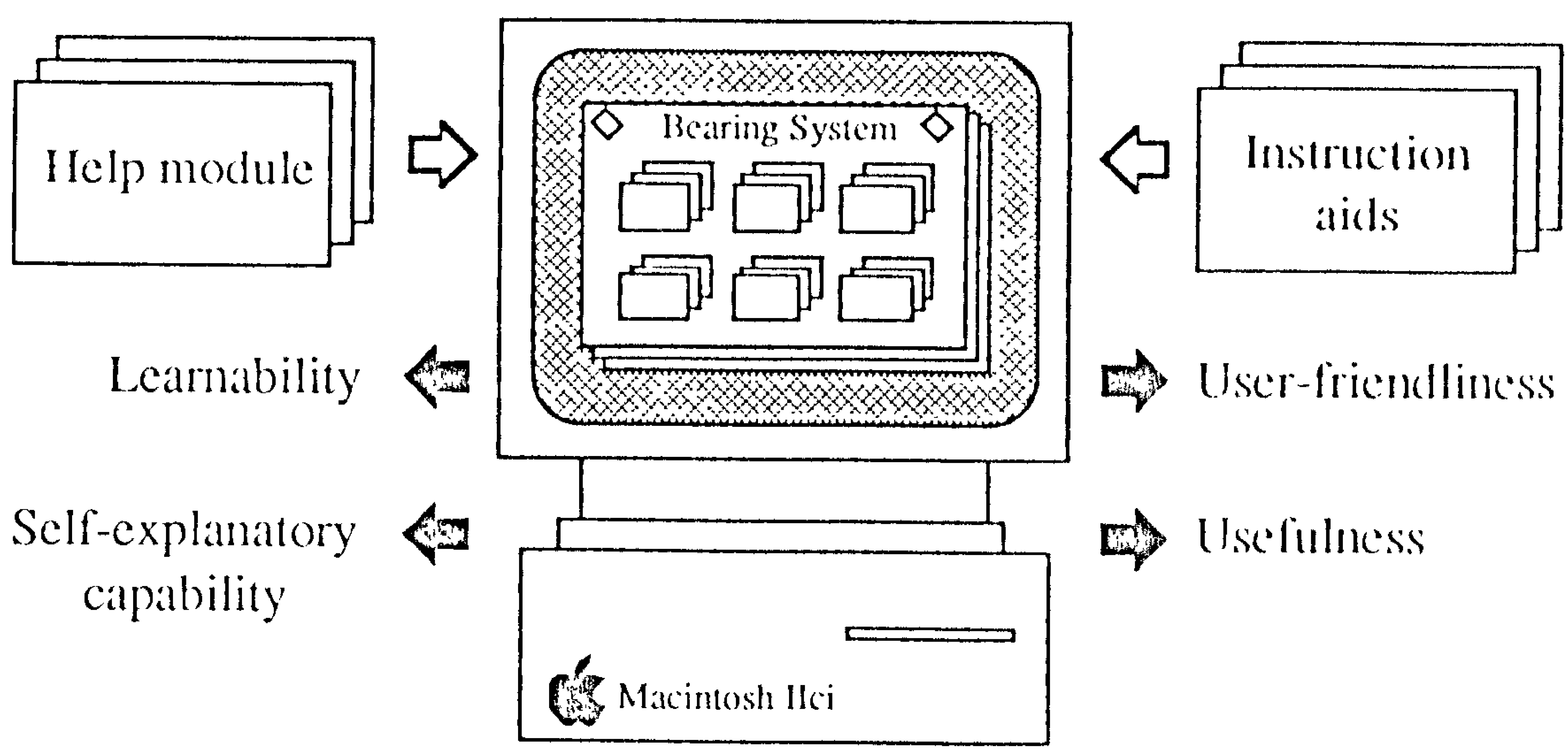


Figure 8.5 User-system interaction support

The design instruction aids use a knowledge-based system approach. The aids support the full design procedure, i.e. from the initial determination of values of bearing parameter, through the monitoring of the computed parameter values, to the final evaluation of the design values. As shown in Figure 8.6, for example, there are various bearing parameters and value fields on the design input card. The designer can input selected values to the parameter fields. The system responds to the input, makes suggestions to the designer and provides an evaluation of the input. For instance, when the designer moves the mouse to the 'Power ratio' field and clicks it prior to typing a value in the field, the system first responds to the input by making a suggestion for the input value inside the upper rectangular field as shown in Figure 8.6. If the value typed by the designer is outside the normal range, the system will give an evaluation inside the rectangular field together with an audible warning sound. The controlling intelligence for the input to the field is rule-based.

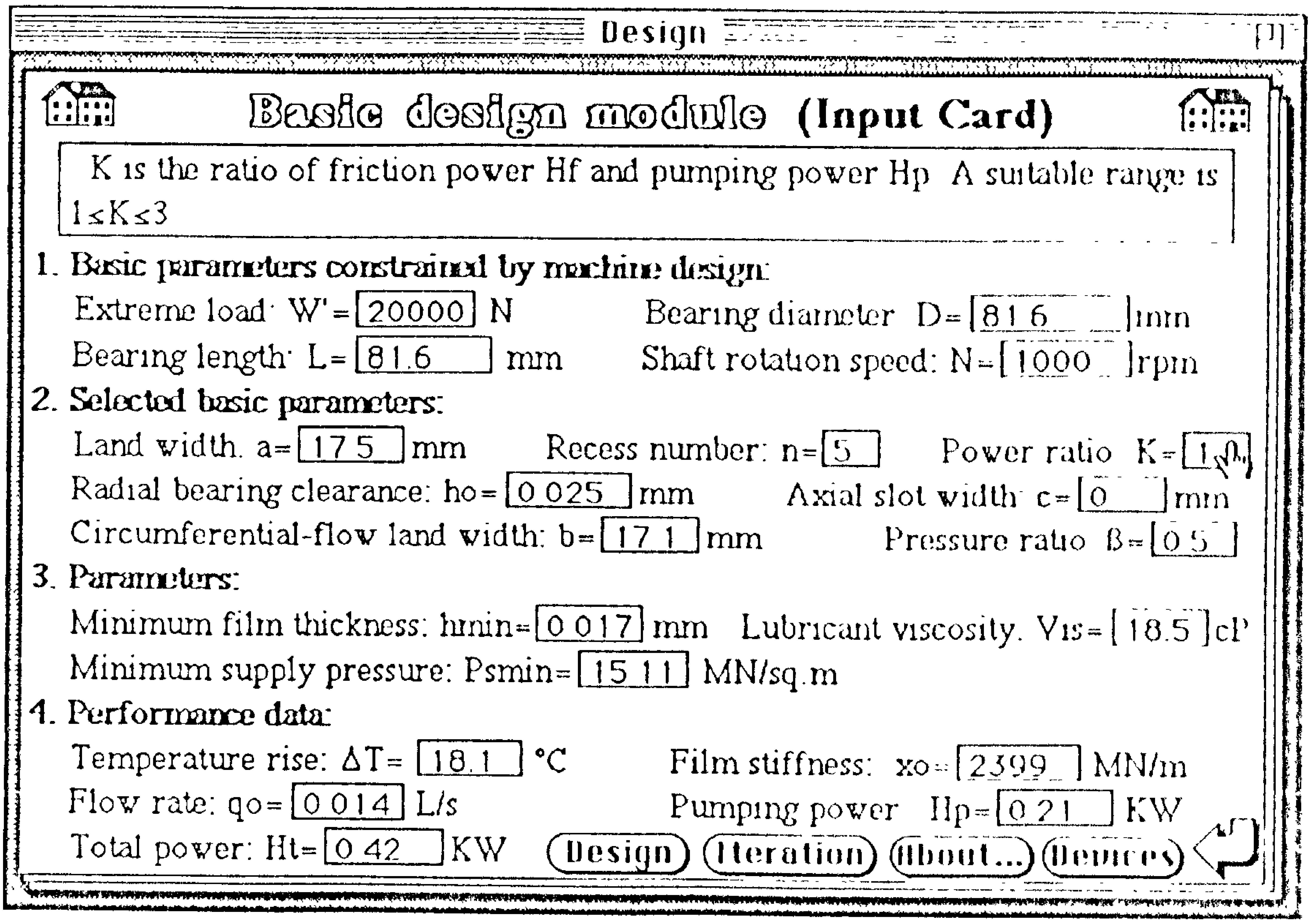
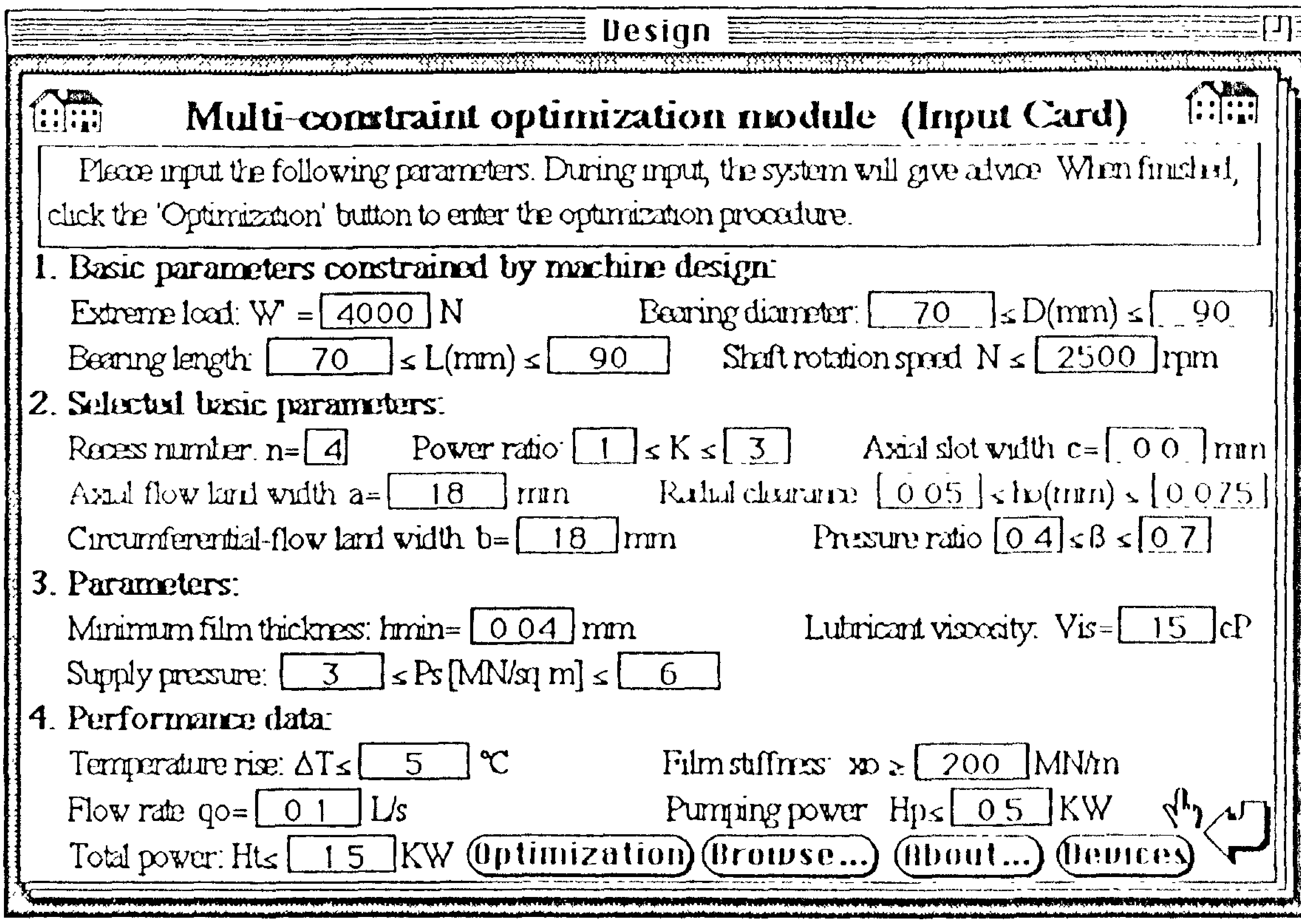
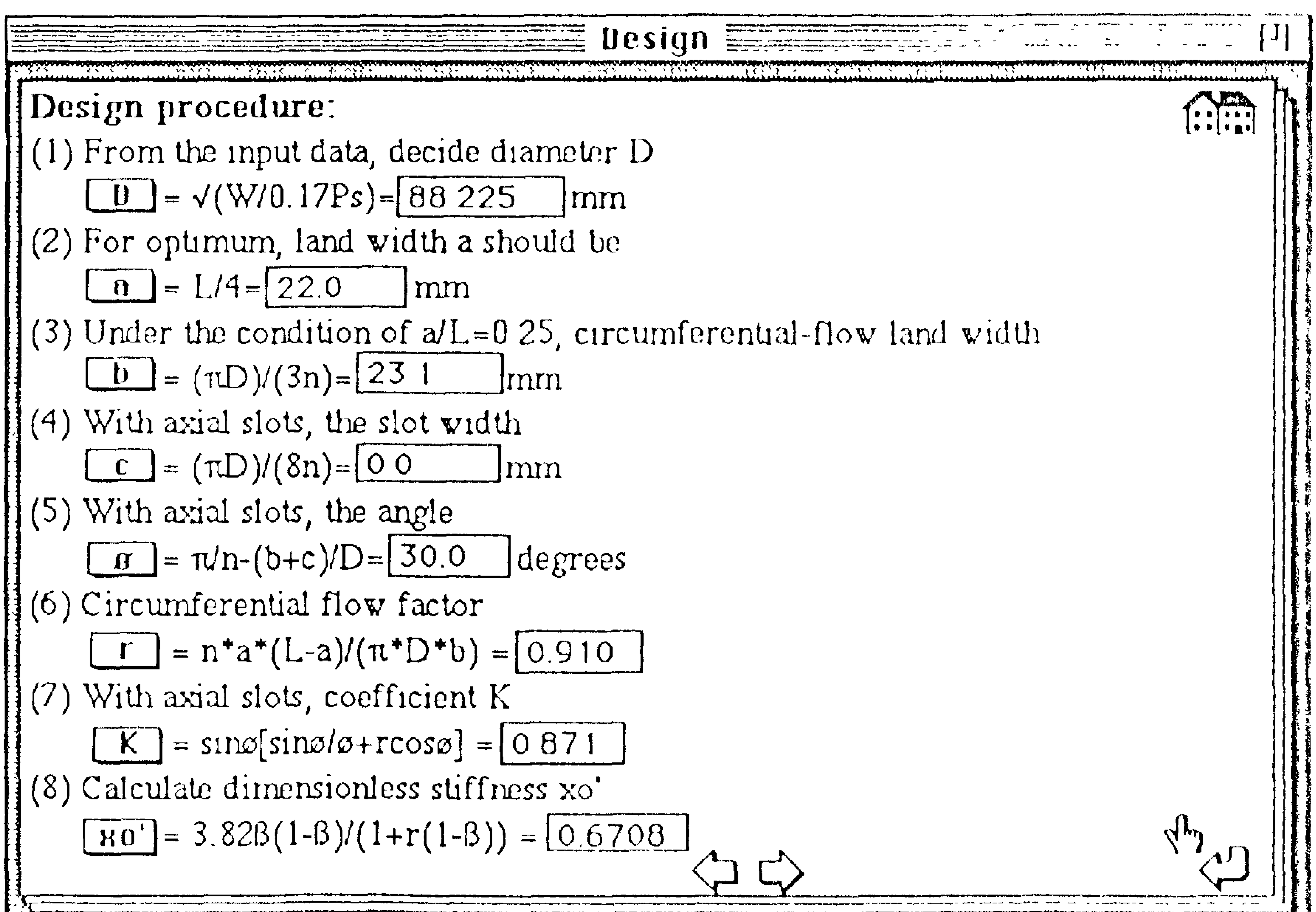


Figure 8.6 The design input card in the design module

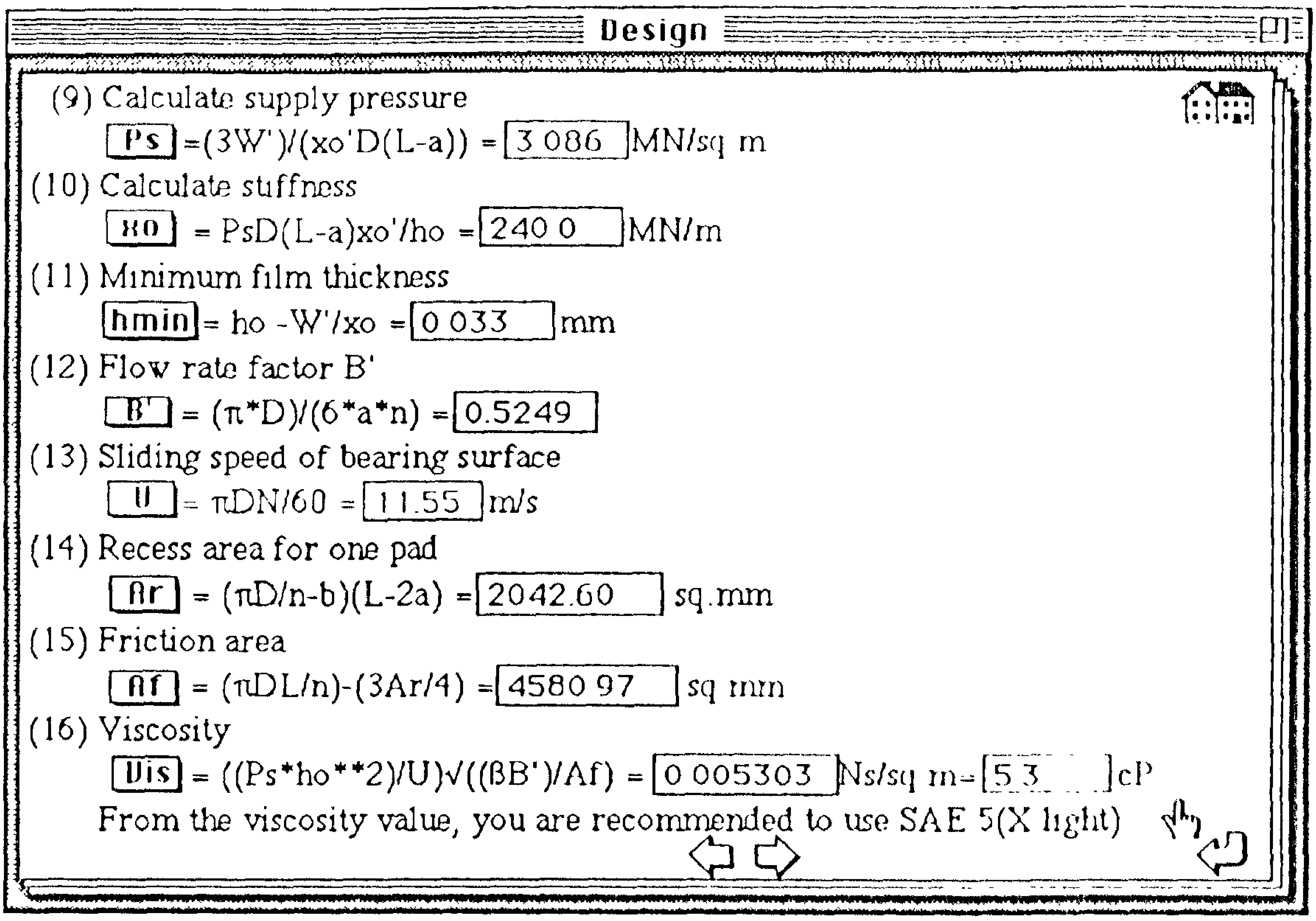
As with the 'Power ratio' field, the input process for other bearing parameter fields operates in a similar mode. The intelligence is rule-based even though there may be a different number of rules for different bearing parameters. The interaction aids for monitoring the design computing process and design parameters evaluation are also developed using the production rules approach. Knowledge-based HCI can assist a user to interact with the system both effectively and efficiently[94].

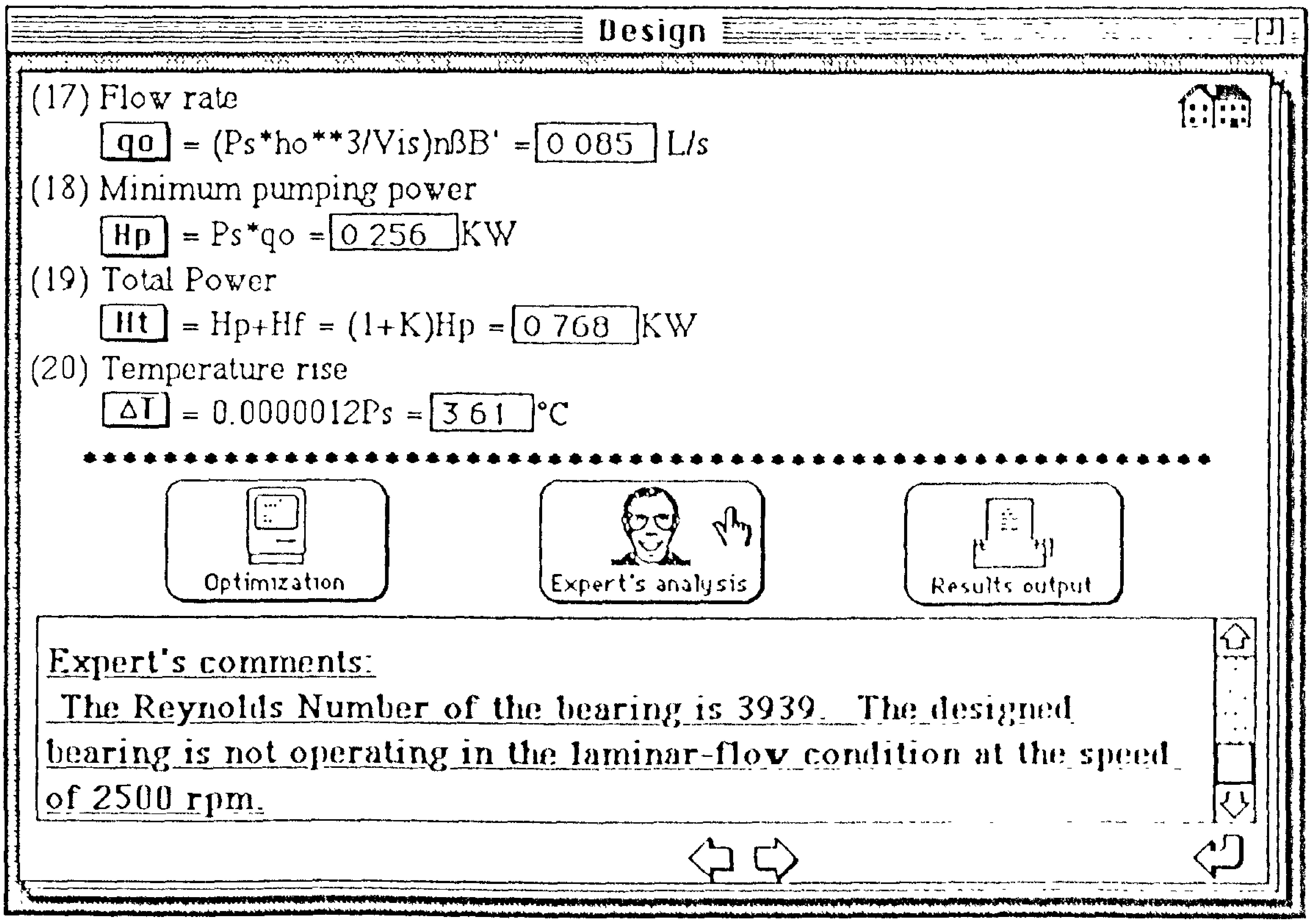

Design
Multi-constraint optimization module (Input Card)
Please input the following parameters. During input, the system will give advice. When finished, click the 'Optimization' button to enter the optimization procedure.
1. Basic parameters constrained by machine design:
Extreme load: W' = 4000 N
Bearing diameter: 70 ≤ D(mm) ≤ 90
Bearing length: 70 ≤ L(mm) ≤ 90
Shaft rotation speed N ≤ 2500 rpm
2. Selected basic parameters:
Recess number n= 4
Power ratio 1 ≤ K ≤ 3
Axial slot width c= 0.0 mm
Axial flow land width a= 18 mm
Radial clearance 0.05 ≤ ho(mm) ≤ 0.075
Circumferential-flow land width b= 18 mm
Pressure ratio 0.4 ≤ ß ≤ 0.7
3. Parameters:
Minimum film thickness: hmin= 0.04 mm
Lubricant viscosity: Vis= 15 cP
Supply pressure: 3 ≤ Ps [MN/sq m] ≤ 6
4. Performance data:
Temperature rise: ΔT≤ 5 °C
Film stiffness: xo ≥ 200 MN/m
Flow rate qo= 0.1 L/s
Pumping power Hp≤ 0.5 KW
Total power: Ht≤ 1.5 KW
Optimization
Browse...
About...
Devices

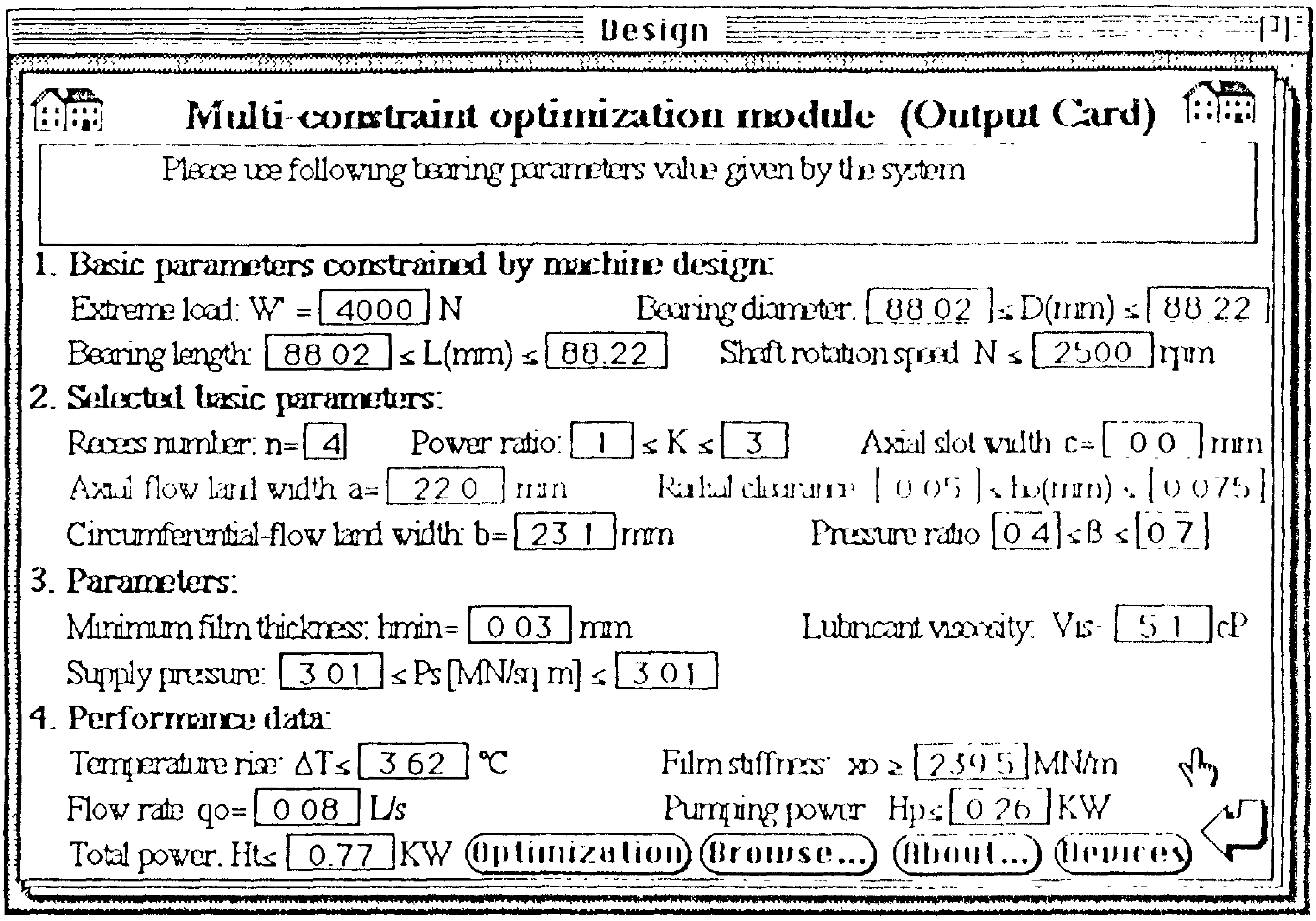
(a)


Design
Design procedure:
(1) From the input data, decide diameter D
D = √(W/0.17Ps)= 88.225 mm
(2) For optimum, land width a should be
a = L/4= 22.0 mm
(3) Under the condition of a/L=0.25, circumferential-flow land width
b = (πD)/(3n)= 23.1 mm
(4) With axial slots, the slot width
c = (πD)/(8n)= 0.0 mm
(5) With axial slots, the angle
ø = π/n-(b+c)/D= 30.0 degrees
(6) Circumferential flow factor
r = n*a*(L-a)/(π*D*b) = 0.910
(7) With axial slots, coefficient K
K = sinø[sinø/ø+rcosø] = 0.871
(8) Calculate dimensionless stiffness xo'
xo' = 3.82ß(1-ß)/(1+r(1-ß)) = 0.6708

(b)


Design
(9) Calculate supply pressure
Ps =(3W')/(xo'D(L-a)) = 3.086 MN/sq m
(10) Calculate stiffness
xo = PsD(L-a)xo'/ho = 240.0 MN/m
(11) Minimum film thickness
hmin = ho -W'/xo = 0.033 mm
(12) Flow rate factor B'
B' = (π*D)/(6*a*n) = 0.5249
(13) Sliding speed of bearing surface
U = πDN/60 = 11.55 m/s
(14) Recess area for one pad
Ar = (πD/n-b)(L-2a) = 2042.60 sq.mm
(15) Friction area
Af = (πDL/n)-(3Ar/4) = 4580.97 sq mm
(16) Viscosity
Vis = ((Ps*ho**2)/U)√((ßB')/Af) = 0.005303 Ns/sq m= 5.3 cP
From the viscosity value, you are recommended to use SAE 5(X light)
(c)


Design
(17) Flow rate
qo = (Ps*ho**3/Vis)nßB' = 0.085 L/s
(18) Minimum pumping power
Hp = Ps*qo = 0.256 KW
(19) Total Power
Ht = Hp+Hf = (1+K)Hp = 0.768 KW
(20) Temperature rise
ΔT = 0.0000012Ps = 3.61 °C
Optimization
Expert's analysis
Results output
Expert's comments:
The Reynolds Number of the bearing is 3939. The designed bearing is not operating in the laminar-flow condition at the speed of 2500 rpm.
(d)



(e)

Figure 8.7 Five cards from the design module for a bearing optimisation.

With the help of rule-based interaction aids, the system design manipulation has an open ended style which allows a user to interact in an easy manner with the system and to achieve a better understanding of the design process. Figure 8.7, shows five procedure cards from a bearing optimal design. A designer can directly define the bearing dimensional and operational conditions constrained by the machine on the input card The designer can also interactively choose the initial values of basic parameters. On the design procedure cards, parameter fields and buttons are available for a designer to activate. A designer can manually interact with the system by using a mouse for the calculation of parameter values. The designer may use the cards as an exercise board for design calculations even though the calculation can also be carried out in an automatic way. When a designer clicks the 'Optimization' button on the input card to enter the optimisation procedure, the system first shows a dialog window asking the designer to input the number of computational iterations. The system will carry out the optimisation iteration cycle according to the number of times indicated by the input value. During the iteration, if a computed parameter value is outside of the range defined by the constraint conditions, the system will pause the iteration and give a warning window and an alerting sound. Figure 8.8 shows a warning window generated during the optimisation process. The system tells the designer which calculated parameter value is outside the constraint range, and asks whether to continue the optimisation process or to stop. It is possible that the constraints on the parameters values may not be suitable. The designer can click the 'Continue' button to continue the

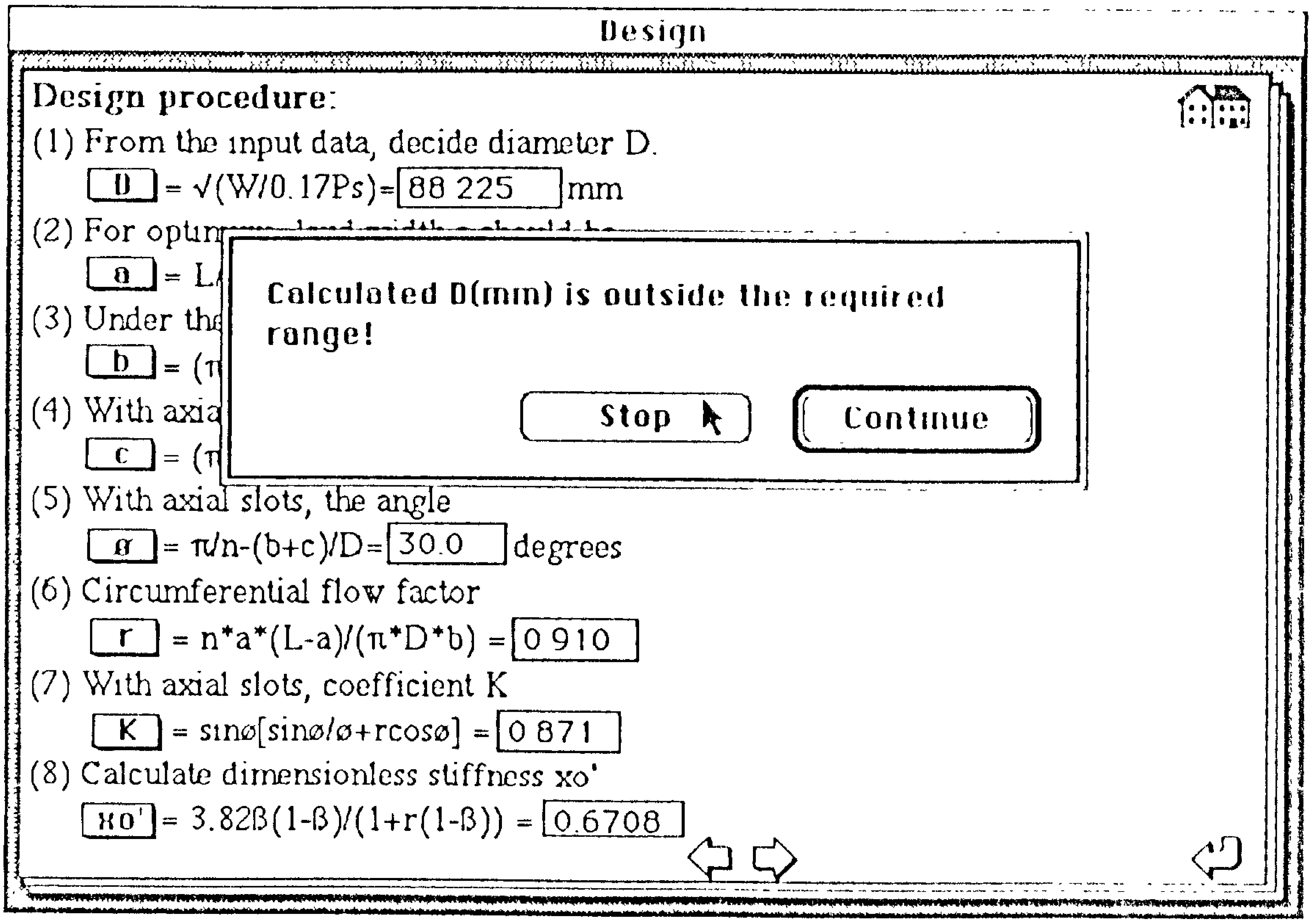


Figure 8.8 A warning window given by the system

optimisation process. If the designer clicks the 'Stop' button, the system will stop the process and display a window in which the system shows its reasoning on the modification required. A reasoning window is shown in Figure 8.9. When the optimisation accuracy is achieved, the system stops the iteration and displays a notice window as shown in Figure 8.10 together with a short burst of light music. The designer can read the optimised values from the output card. This kind of open ended computing provides a designer more freedom to overview and hence understand the design procedure. A designer can intuitively overview the design process and learn to

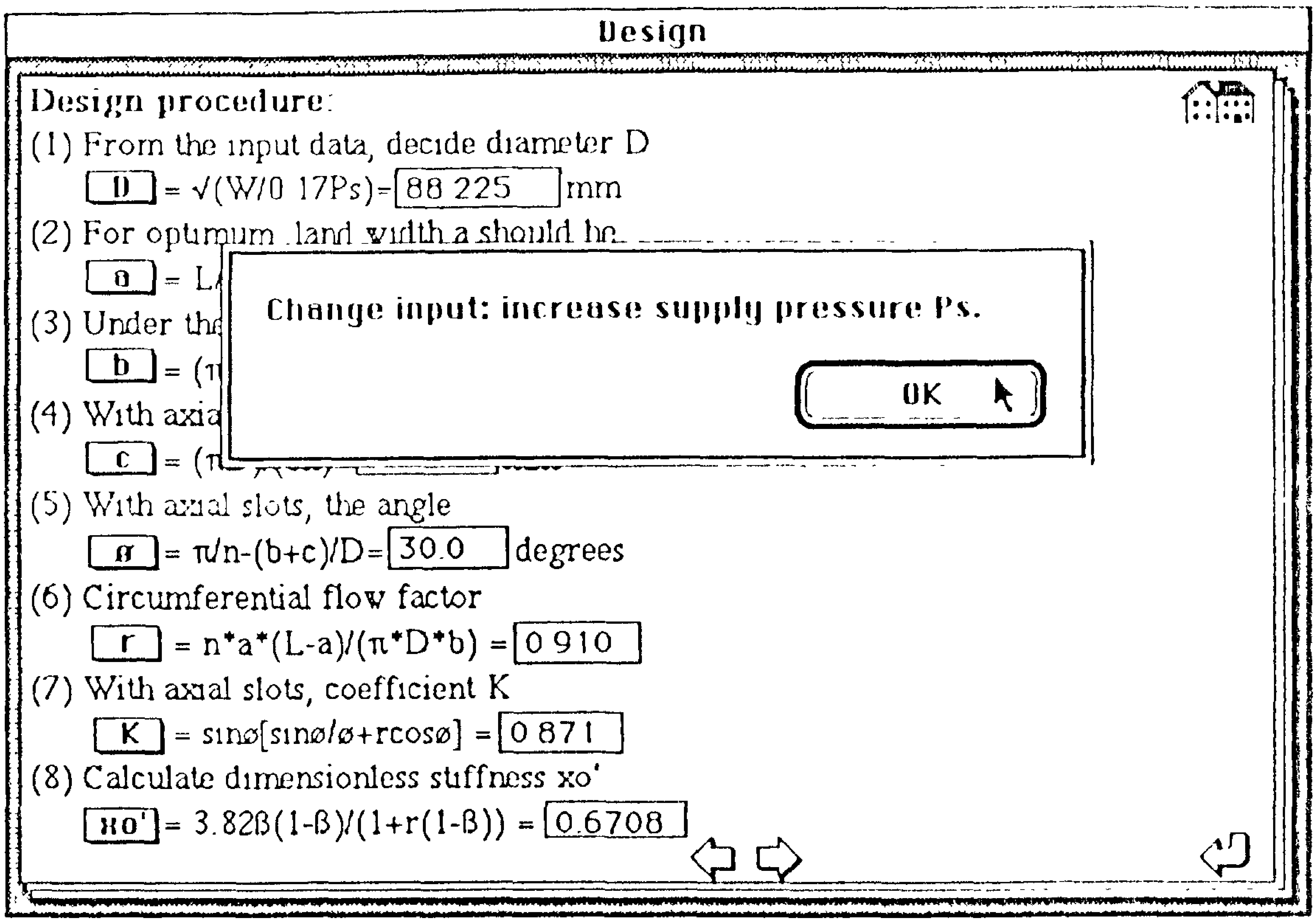


Figure 8.9 A reasoning window given by the system

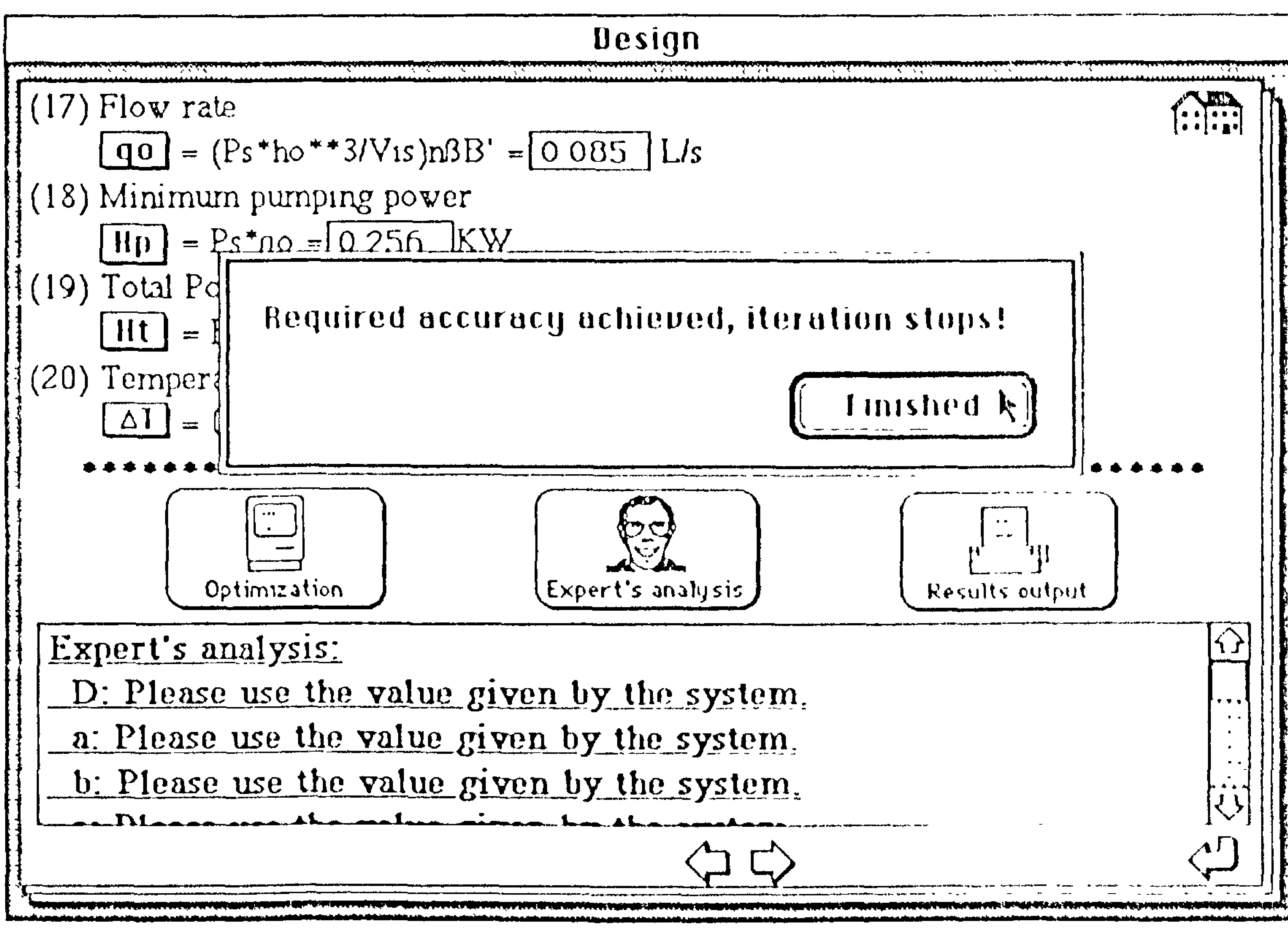


Figure 8.10 A design completion notice window given by the system

control the process interactively.

8.5 System evaluation

8.5.1 Evaluation method

The system evaluation is an intrinsic element within the system development. The evaluation is an iterative process throughout each phase of the system design and development. Even so, a comprehensive evaluation, with particular reference to the system functionality, is required towards the end of the system development process. The system evaluation described as follows is related to this latter stage.

Based on the literature survey and discussions with academic staff and other engineers, the following evaluation criteria were established[95]~[100]:

(a) Functionality: The system should meet the needs and requirements of users when they carry out realistic design tasks.

(b) Consistency: The way the system looks and works should be consistent and compatible with user conventions and expectations.

(c) Explicitness: The way the system works and is structured should be clear to the user.

(d) Visual clarity: Information displayed on the screen should be clear , well organised, unambiguous and easy to read.

(e) Flexibility: The system should be sufficiently flexible in structure to allow for system expansion and updating.

(f) Error prevention: The system should be designed to minimise the possibility of user errors, with inbuilt facilities for detecting and handling those which do occur. Users should be able to check their inputs and to correct errors or potential error situations before the design task is completed.

(g) User guidance and control: Informative, easy-to-use and relevant guidance and support such as on-line help and informative feedback should be provided to help the user understand and use the system.

(h) Efficiency: The system should be efficient in terms of speed and storage requirements

(i) Cost-effectiveness: The system should provide the user with effective design support with low cost in implementation and operation.

Each of these criteria will be then translated into a checklist. The checklist forms the core of the evaluation method, and comprises specific questions or requirements about features of the system in relation to a particular criterion. For instance, the criterion of consistency incorporates a number of questions concerned with the consistency of formatted text, menu structure, action sequences, use of icons and screen format, etc.

Following the checklists, a systematic evaluation will be carried out. The evaluation will concern with all aspects of the system based on the evaluation criteria and checklists. Figure 8.11 illustrates the framework of the system evaluation.

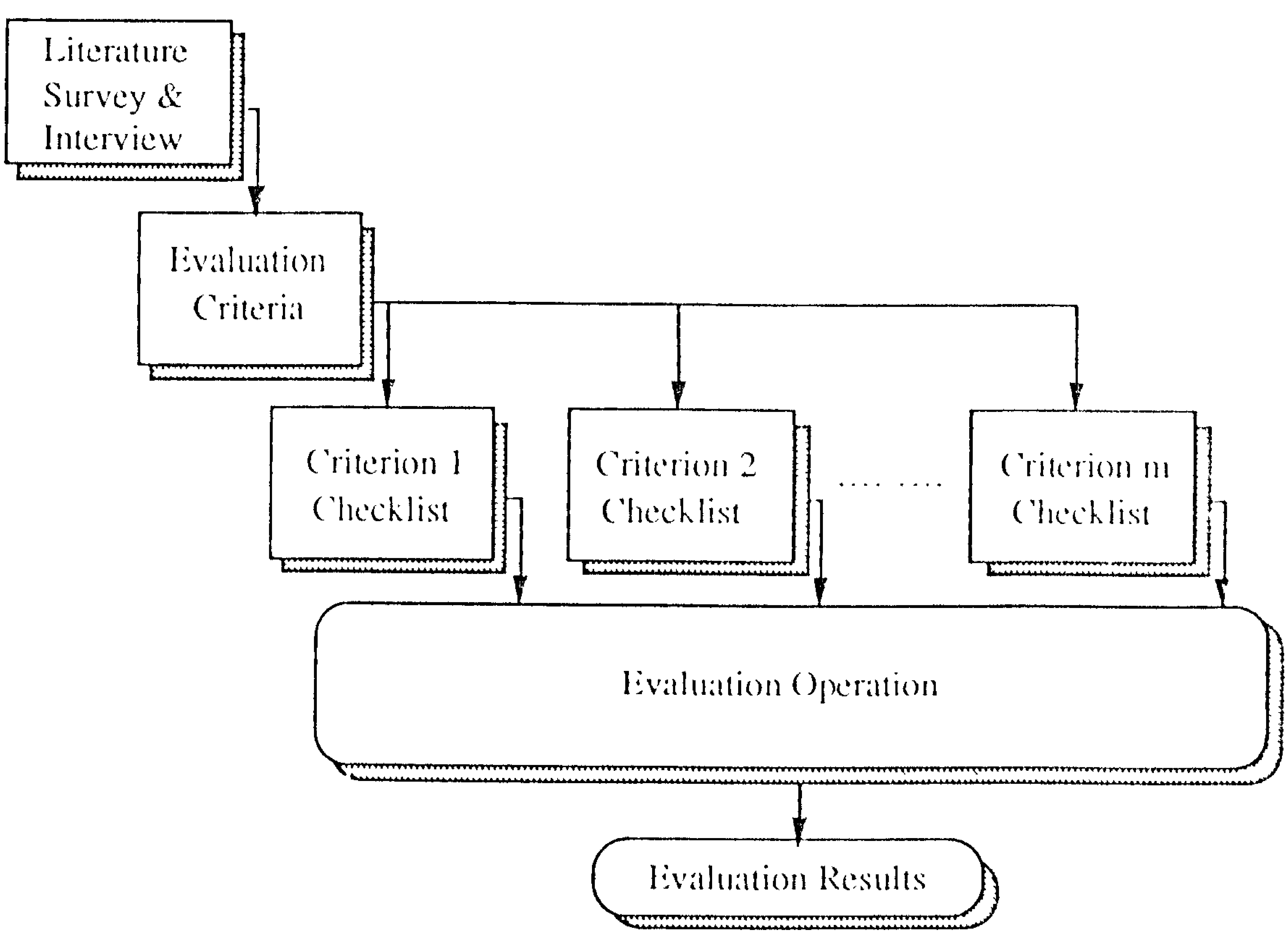


Figure 8.11 The framework of the system evaluation

As shown in Figure 8.11, a comprehensive evaluation of the system requires a multi-disciplinary approach and ideally needs support from cognitive scientists, psychologists, graphic designers and users. A comprehensive evaluation will be a time consuming and expensive process. At the time of writing the thesis, a comprehensive evaluation has not been undertaken except for the work on the system functionality testing.

8.5.2 Functionality evaluation

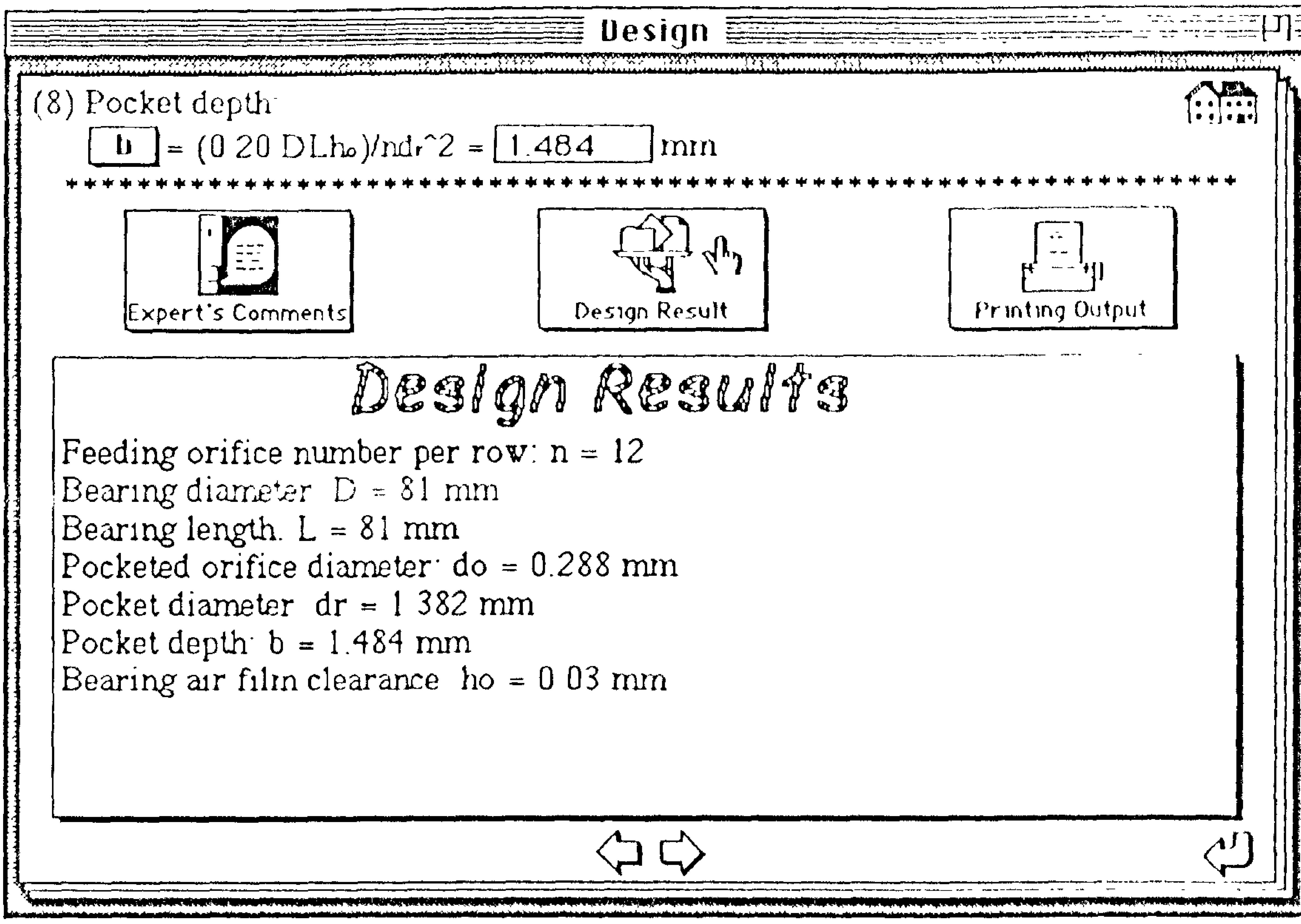
So far, the system evaluation has mainly concentrated on the system functionality. The evaluation was undertaken by using the system to undertake design tasks and test as much of the system's functionality as possible. The following are two evaluation examples of using the system in the design of bearings for machine tools.

(a) Example 1

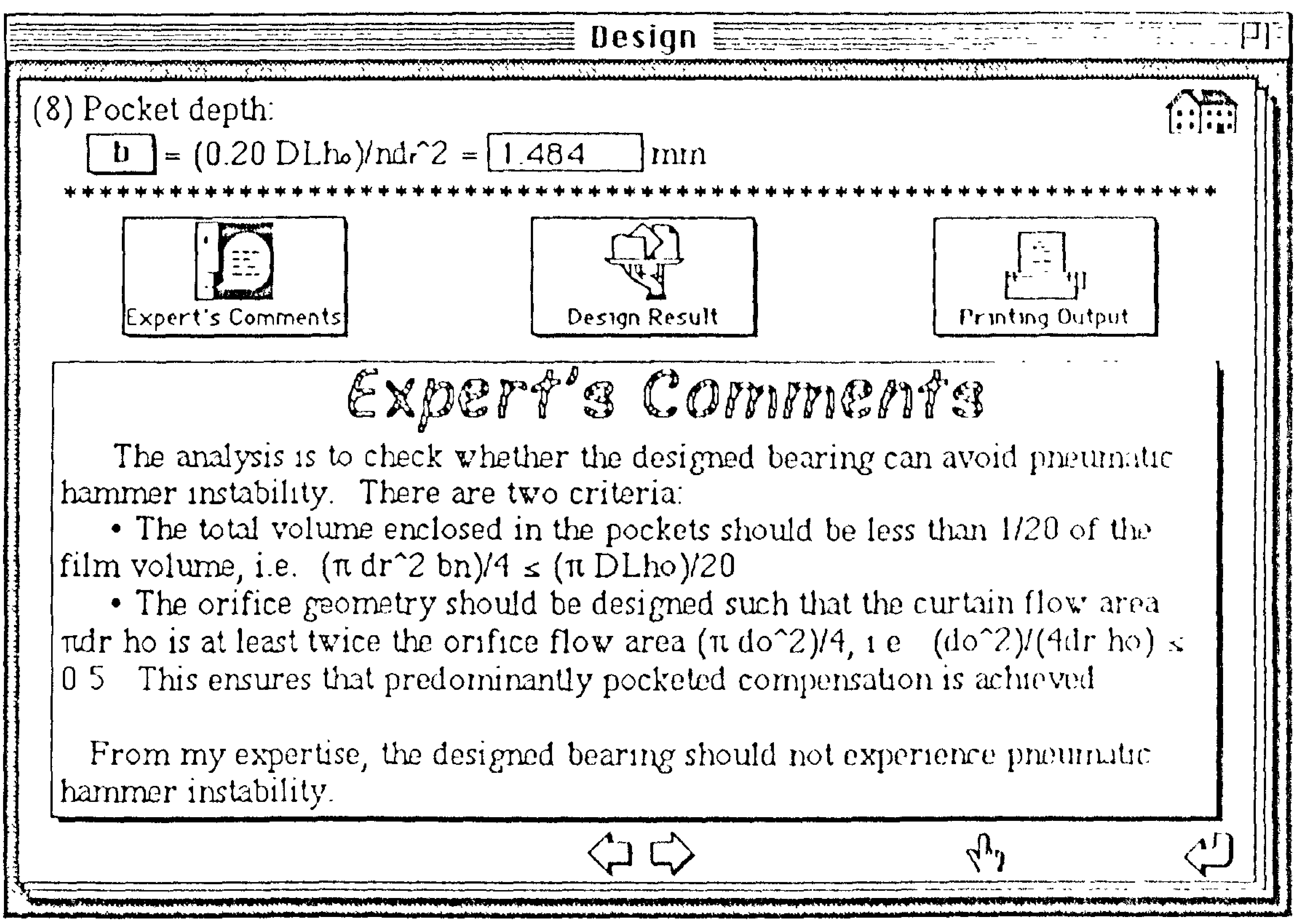
Table 8.1 shows the requirements for a bearing to be used to support the wheelhead

Design requirements
1. Spindle rotation speed: 0 ~ 7,000 r.p.m.
2. Spindle radial error motion: less than 0.4 μm
3. Spindle temperature rise: less than 5 °C
4. Spindle radial stiffness: larger than 100 N/μm
5. Spindle axial stiffness: larger than 50 N/μm
6. Radial load capacity: 1,200 N
7. Axial load capacity: 600 N
8. Contamination to workpiece and surroundings: minimal

Table 8.1 Requirements for a bearing to support a grinding wheelhead spindle



(a)



(b)

Figure 8.12 The design results produced by the system spindle of a cylindrical grinding machine. Based on these requirements, a bearing was designed using the system. The system recommended an aerostatic journal bearing for the application. The bearing configuration selected was a combined journal and thrust configuration with pocketed orifice feed. After the selection, the system design module was used to undertake the design of the bearing and its pocketed orifice. Figure 8.12 shows the design results produced by the system. In the authors judgment, the design results are suitable for the requirements although other answers may be possible. Appendix III illustrates the whole design procedure carried out with the system.

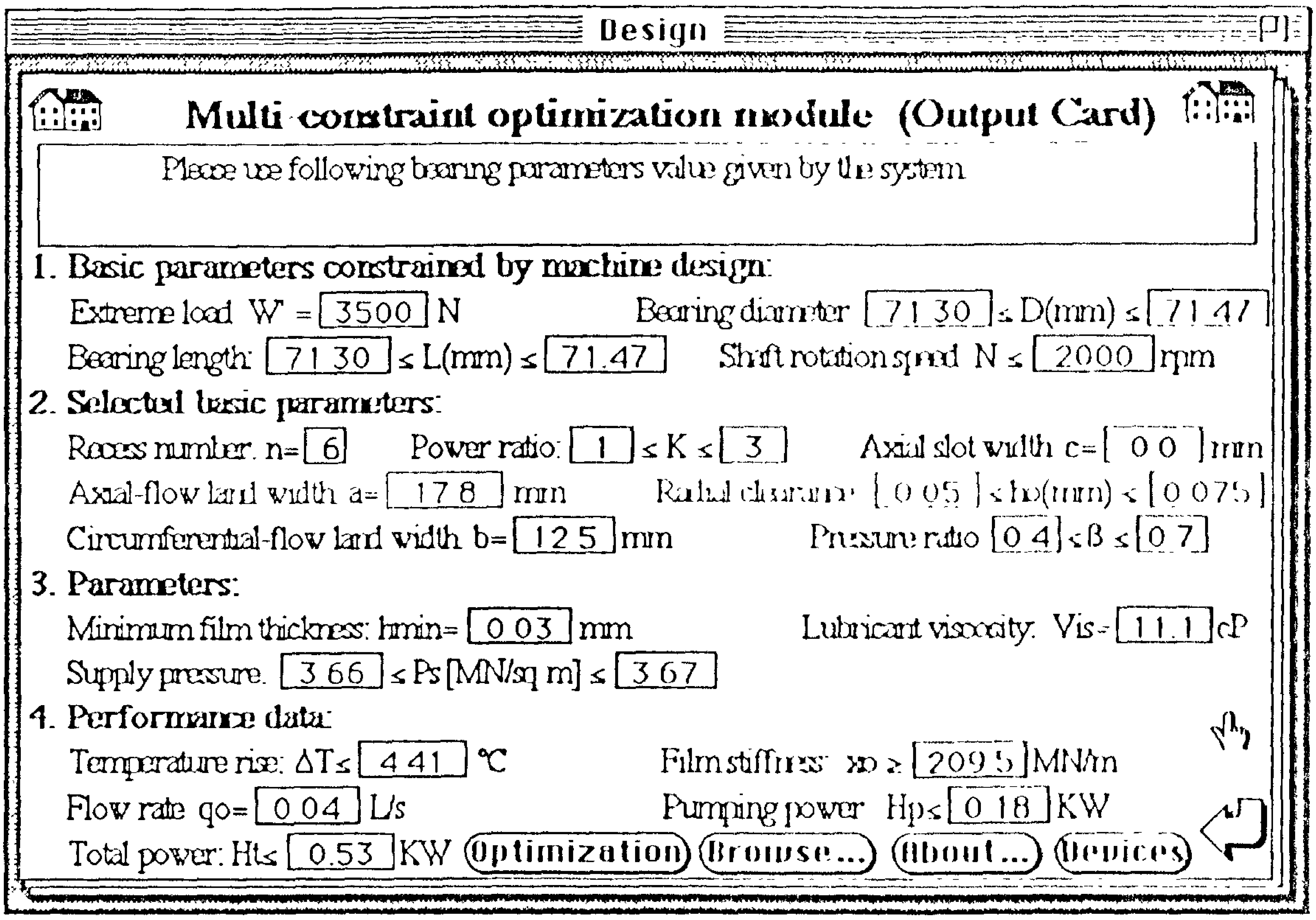
(b) Example 2

Table 8.2 illustrates another requirements for a bearing to support the spindle of a

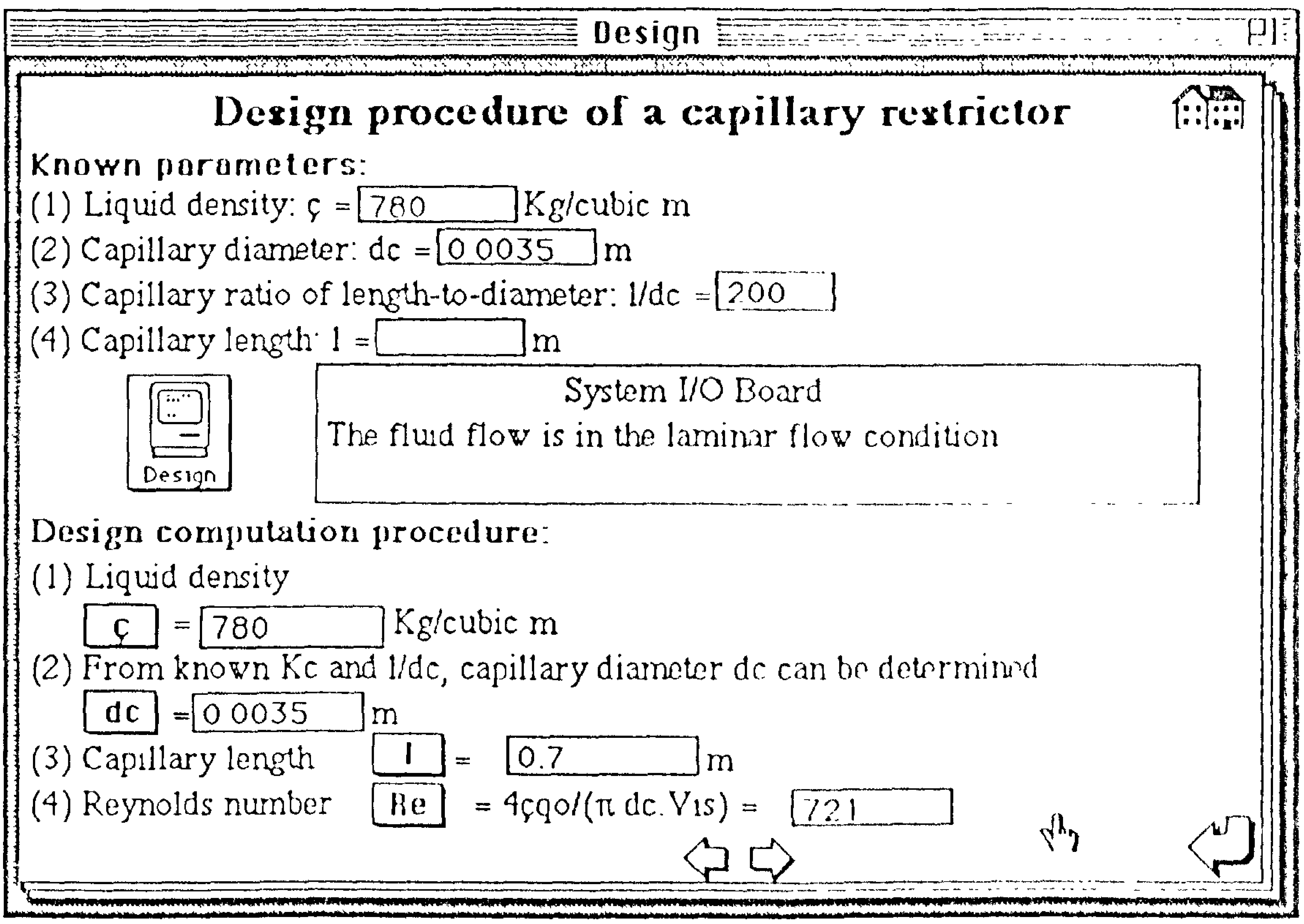
Design requirements
1. Spindle maximum rotation speed: 2,000 r.p.m.
2. Spindle radial error motion: less than 0.2 μm
3. Spindle temperature rise: less than 5 °C
4. Spindle radial stiffness: larger than 200 N/μm
5. Spindle axial stiffness: larger than 150 N/μm
6. Radial load capacity: 3,000 N
7. Axial load capacity: 1,500 N
8. Bearing dimension: as small as possible

Table 8.2 Requirements for a bearing to support turning machine spindle

precision turning machine. Compared with Example 1, the spindle radial load capacity and stiffness required were much higher, and the spindle maximum rotation speed was much lower. Through a dialogue with the system selection module, a hydrostatic



(a)



(b)

Figure 8.13 The bearing design results produced by the system bearing was recommended for the application. The bearing recommended was a cylindrical recessed journal configuration and capillary restrictor feed. After the selection, the design module was used to carry out the bearing and restrictor design. The design results are illustrated in Figure 8.13. Comparing the design results with the design requirements, it is found that the results are suitable. The whole design procedure is illustrated in Appendix IV.

8.6 User views

A number of pieces of feedback have been collected mainly from the director of studies for the project and from engineers from two software houses, from industry, and staff of Liverpool John Moores University. The feedback was concerned with all aspects of the system such as the user interface design, the system operation, the development platform, the system compatibility and cost. It was found the system needs further development specially in the system HCI aspects. The feedback will be invaluable for further work on the system development and evaluation.

Many criticisms were obtained and used to refine the system. Other criticisms required further development which was too substantial to undertake for the thesis. The most important criticisms were as follows:

(a) The design input/output cards were too crowded (see Appendix III and Appendix IV). This criticism is accepted. However, in order to simplify the layout of these cards would require to rewrite quite a large part of the system programmes. This development is therefore proposed as an aspect for further work. The over crowding of information does not prevent the system being used although clearly the layout is less than ideal.

(b) Three users complained they lost their orientation during using the system.

(c) The system is not integrated with a CAD drawing utility which is needed for the presentation of a bearing design.

(d) Many icons and manipulation buttons are not clear to users. Manipulation icons and buttons should be high-lighted and straight forward for design operations.

(e) An IBM PC version of the system is expected because most engineers are used to IBM PC based packages for their design work Ideally the system would be compatible with PC and workstation platforms.

Part III Extension of the System Technology

Chapter 9 Development of a prototype hypermedia-based engineering design environment - HyperCAD

9.1 Introduction

The computer since its inception has been used as an aid for engineering design. It has been as a calculator, for statistical analysis, for CAD drawing, and for simulation. Early use was mainly concentrated on numerical or algorithmic computations. In the last two decades, however, there has been an increasing application of powerful dedicated design tools. Pressures for change include[101]:

- Market demands for new and better design tools to produce high quality designs quickly and efficiently.
- Competitive pressures require designers to create new type of products and systems continuously. Lead-time is critical and the ability to create new designs becomes very important. Creativity may be improved by a powerful design support system.
- The high performance of modern products is considerably dependent on the incorporation of multi-disciplinary technologies such as mechanics, electronics, and optics. This causes a new problem for the designer that is the need for continual cooperation and mutual understanding between designers from the same or different disciplines.
- Design is integrated much closer with manufacturing. In concurrent engineering, for example, design is recognised as very important in the whole information processing system, and plays a key role affecting the efficiency of the whole manufacturing system.

These changes bring about the requirement for computers to assist designers in an effective, efficient and user-friendly way. The assistance should include not only the conventional features such as computer drawing, design analysis and databases, but also design decision making support such as information retrieval, inferencing and judgment, error diagnosis and communication. It is considered that design aids incorporating AI techniques could be an effective means to meet the challenge of these changing design requirements. AI technologies, such as expert systems and hypermedia, provide the potential to develop a higher level of computer based aid for the engineering designer[101][102].

In recent years, some researchers have tried to integrate hypermedia technology with expert systems in developing computer based design systems[80][103]~[108]. However, the research carried out is quite limited and mainly focuses on the implementation of individual prototype systems relating to specific design applications. A systematic investigation into the application of hypermedia in engineering design is essential. It is necessary, for example, to obtain better understanding of the relationship between the design process and hypermedia semantic networks. It is also necessary to investigate appropriate approaches using hypermedia in computer based design systems, and the possibility of taking hypermedia as a kernel for the development of a design environment.

In this chapter, the development of a prototype hypermedia based design environment - HyperCAD will be described. HyperCAD aims to be a higher level of design aid. HyperCAD uses hypermedia as a link to integrate a variety of design facilities. HyperCAD is designed to integrate a full range of design tools to be accessible for all design phases within one hypermedia-based environment. Because of the associative characteristics of hypermedia, HyperCAD may be also an approach to obtaining a better understanding of the nature and principles of engineering design process.

9.2 An engineering design process model

Design is a creative activity related to products, production processes and more generally of humanity serving systems using available materials, products and processes. Design aims to achieve a specific function, responding to the demand of the costumer and achieve compromises between conflicting constraints such as cost, delivery, delay, feasibility and maintainability[109]. Design can be defined as the use of scientific principles, technical information and imagination in the definition of a mechanical structure, machine or system to perform prespecified functions with the maximum economy and efficiency[110].

In defining an engineering design process, two approaches are possible. One approach is to look at the life cycle of the product from conception to retirement, which is usually referred to as the morphology of the design process[111]. As shown in Figure 9.1, the design morphology consists of six phases which are needs analysis, feasibility study, conceptual design, detailed design, production, and distribution and consumption. In the production phase the product first appears as a physical reality. If the planning for this and subsequent phases of the product life proves to be inadequate, the designer may be called on to modify or to completely redesign the product. Modifications are normally undertaken based on feedback as shown in Figure 9.1.

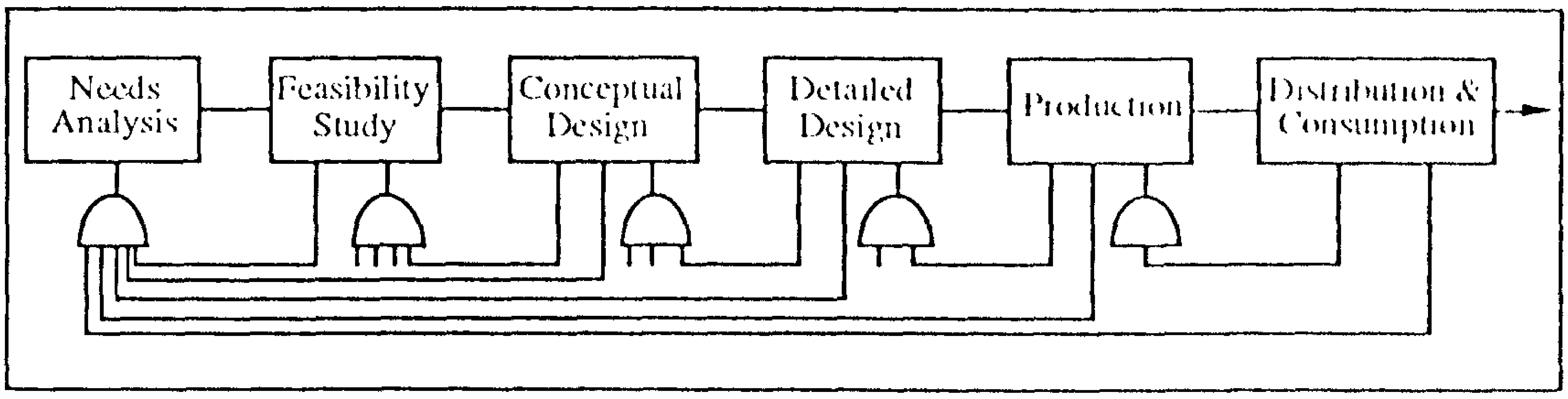


Figure 9.1 The morphology of the design process

The second method of describing the design process involves a detailed examination of the designer's actions as the designer goes about identifying and solving his problem. This results in what is called the anatomy of design and may be repeated many times for each phase in the life cycle of the design product[111]. Starting with the clear recognition and definition of the prime need, the anatomy of design leads to the final point at which the designer releases his plans for implementation. Figure 9.2, illustrates the main steps which characterise the anatomy of the design process.

Although there are different ways of describing the design process, the aim of the process is to create a product which satisfies customer needs[68]. In the past, the major emphasis in design has been on functional performance and aesthetics. Recently, with the popular applications of computers, activity has been directed toward other goals such as design for manufacture[112], design for improved assembly[113], design for the life cycle[114], design for costs[115], and design for simplified analysis[116]~[118]. In all of these, the computer is playing an ever increasing role and taken as a bridge to link the design much closer to the product analysis, manufacture, assembly, leading time and costs. Computer-based design is being extended as a comprehensive concept compared with the traditional design approach[119].

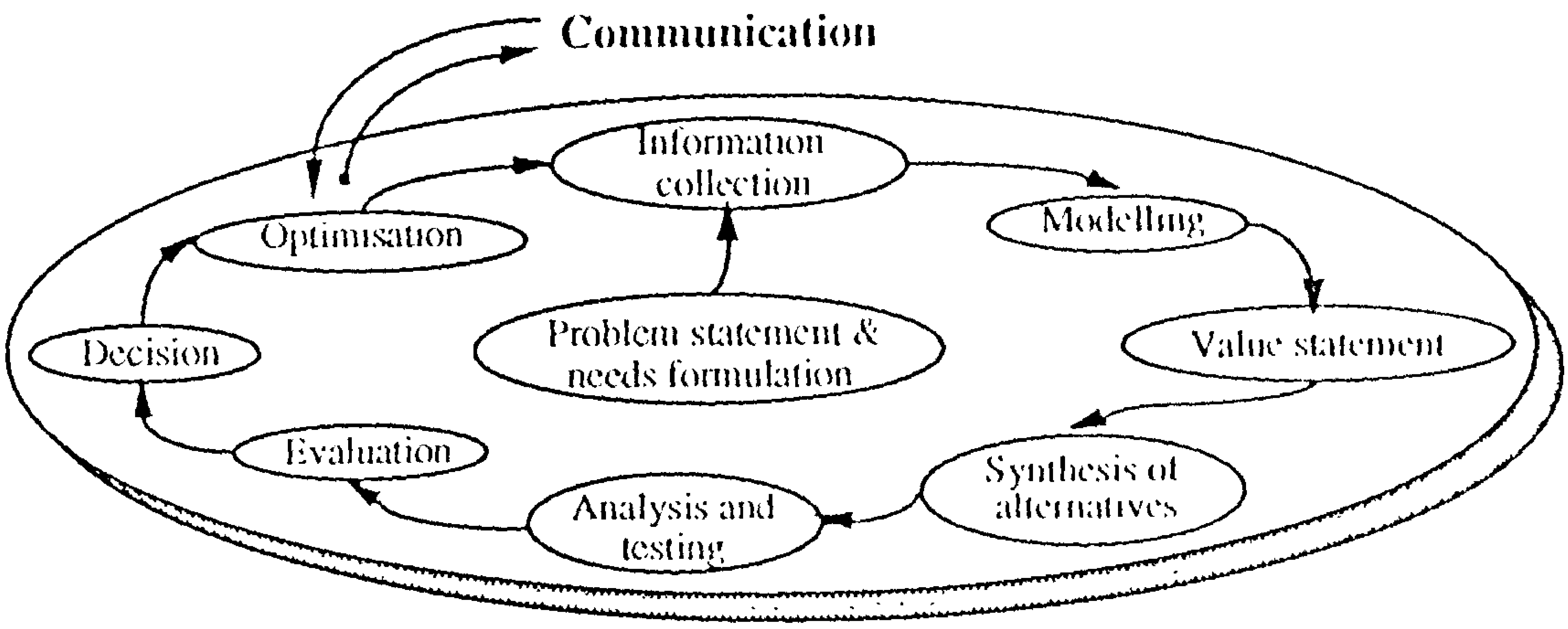


Figure 9.2 The anatomy of the design process

The morphology, anatomy and objective of the design process can be presented together in a three dimensional design matrix as shown in Figure 9.3. This matrix gives a panoramic view of an engineering design process. It should be possible to identify any design action as corresponding to some position in the matrix. The life cycle morphology, the anatomy of design activities, and the design objectives are organically combined together during the design process to meet the design goal. Each step of a morphological phase points to problems which need to be solved; anatomical operations are necessary at each step to cope with the problems. The design matrix is a well defined model which can describe any design process from that of a simple component to that of a complicated system. The model includes issues of both conventional descriptive and prescriptive models of a design process. The physical implementation of the model needs to take place on a computer because of the complexity of information processing.

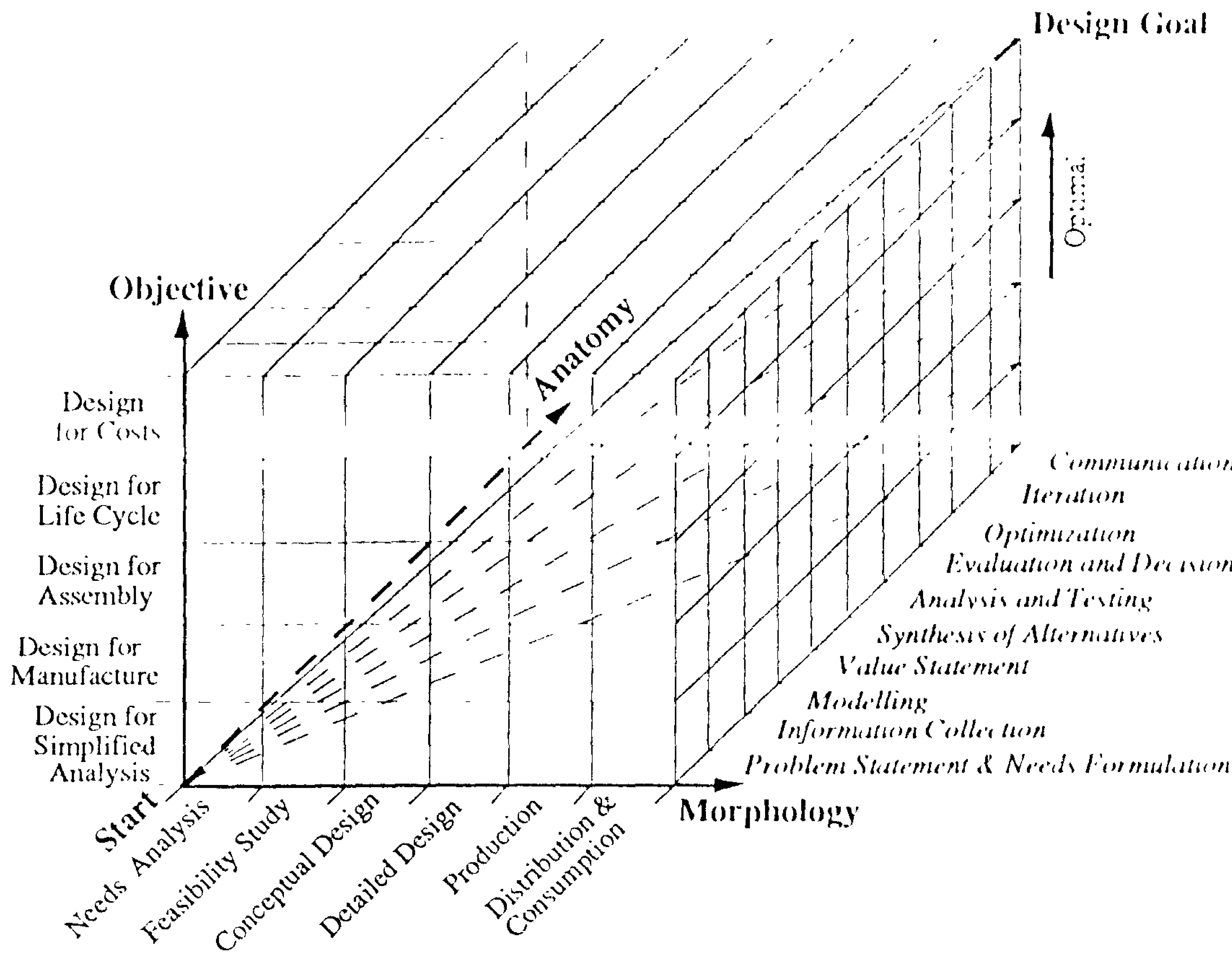


Figure 9.3 Three dimension design matrix

The matrix model illustrated in Figure 9.3 is also of significance in its identification of a design methodology. Figure 9.4 shows the flow chart of a possible design methodology based on the model. The methodology takes morphological phases of a design process as a spine and anatomical operations within or between each phase as linkages for the phases. At each phase, there are a variety of decisions to be made to achieve the design goals. The design model and its explanatory methodology is the basis for the development of HyperCAD.

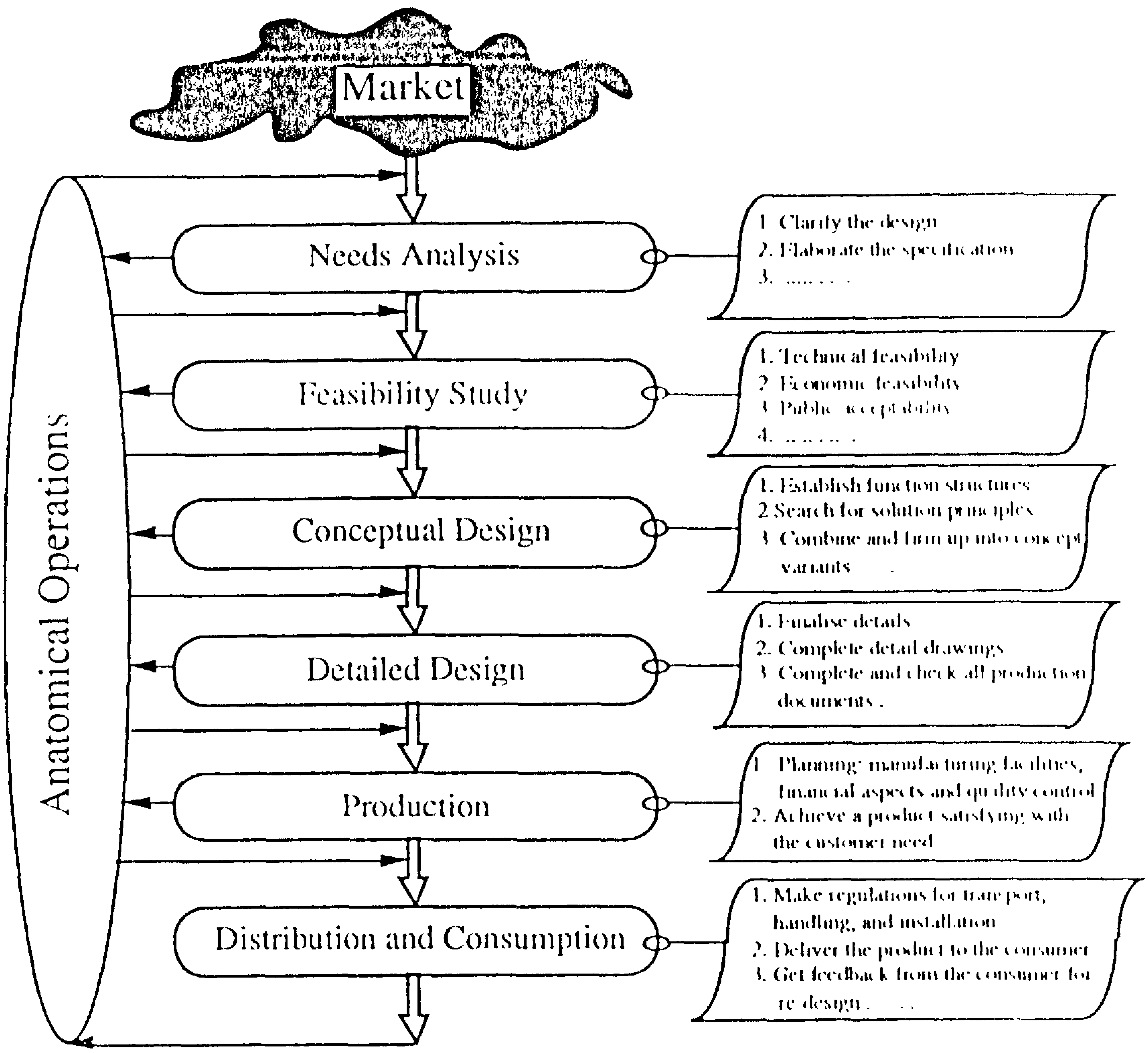


Figure 9.4 The flow chart of a design methodology

9.3 Development of HyperCAD

9.3.1 Developing philosophy

The design matrix model and its interpreted design methodology described in section 9.2 is a comprehensive approach for general engineering design. However, computerised implementation will be very difficult using conventional programming techniques. It would be extremely time-consuming and expensive to implement the model on a software system to cope with all problems. In practice, the designer needs to be able to choose which tools are required to meet his or her needs.

As shown in Figure 9.5, there are a variety of techniques or tools which may be used in

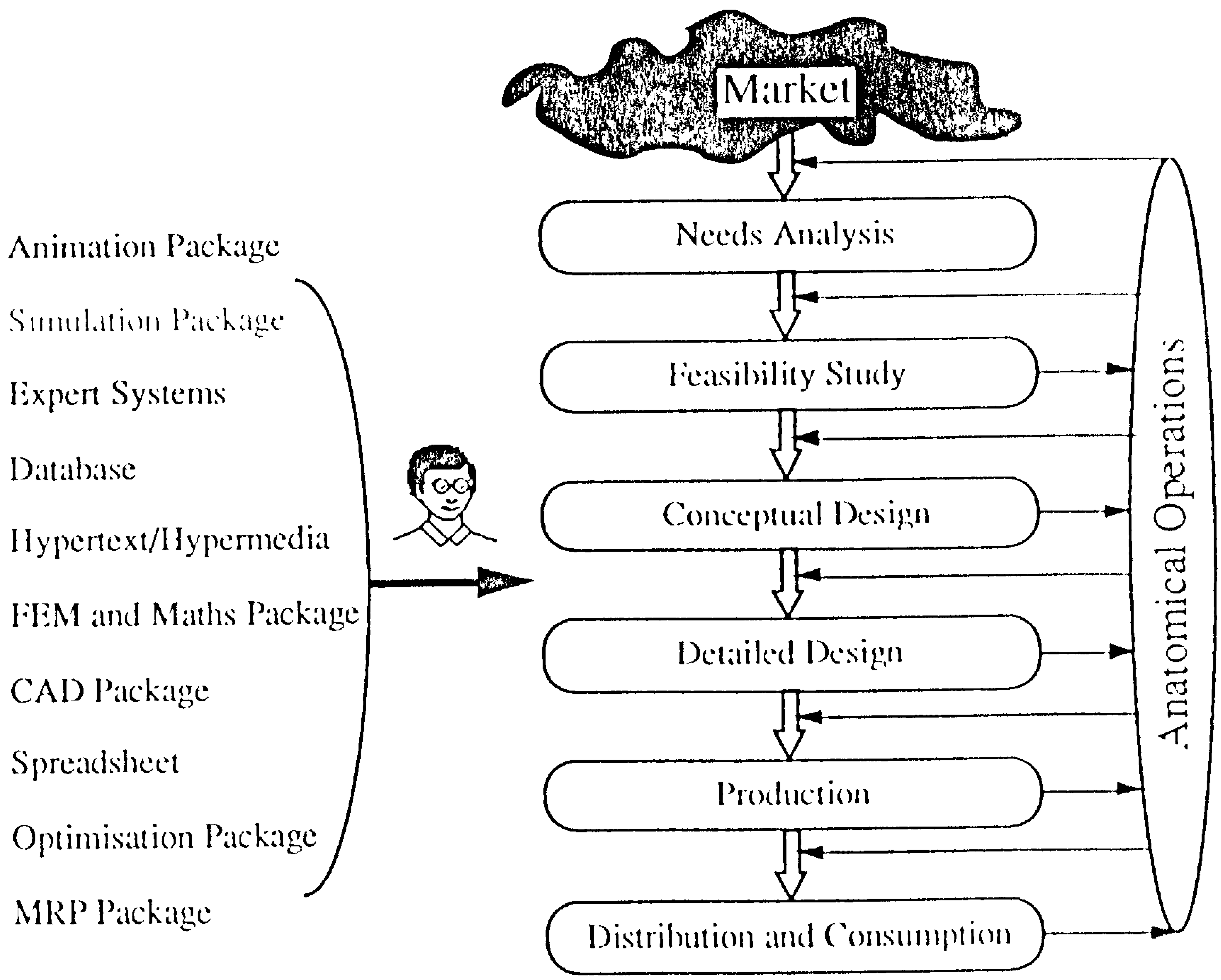


Figure 9.5 Design aids used for engineering design

design. This is not a comprehensive list. It is only intended to indicate the diversity of tools used. However, each technique or tool is normally used separately by a designer to tackle one or more problems. Design ideas or data cannot always be automatically transferred and inherited from one design stage to another using these tools. Designers use these aids or techniques continuously to work on a design task. Within the design process, a designer has to keep his mind open to new design ideas, to mediate the ideas and maintain the ideas as seed development until the realisation of the eventual design goal. Designers are at the centre of all design activities. It is proposed that there should be one system able to provide intelligent support for the designer capable of incorporating many different tools. The design environment should be able to provide full support for the design process through the accessibility of the aids within one environment.

The underlying philosophy of HyperCAD is the use of a hypermedia tool as a vehicle to integrate a variety of design aids or techniques which the designer can choose to form a hypermedia-based macro design environment. Hypermedia is an attractive information management and storage tool because of its associative linkage characters. Figure 9.6 shows the structural scenario of HyperCAD. The hypermedia forms the basis of the

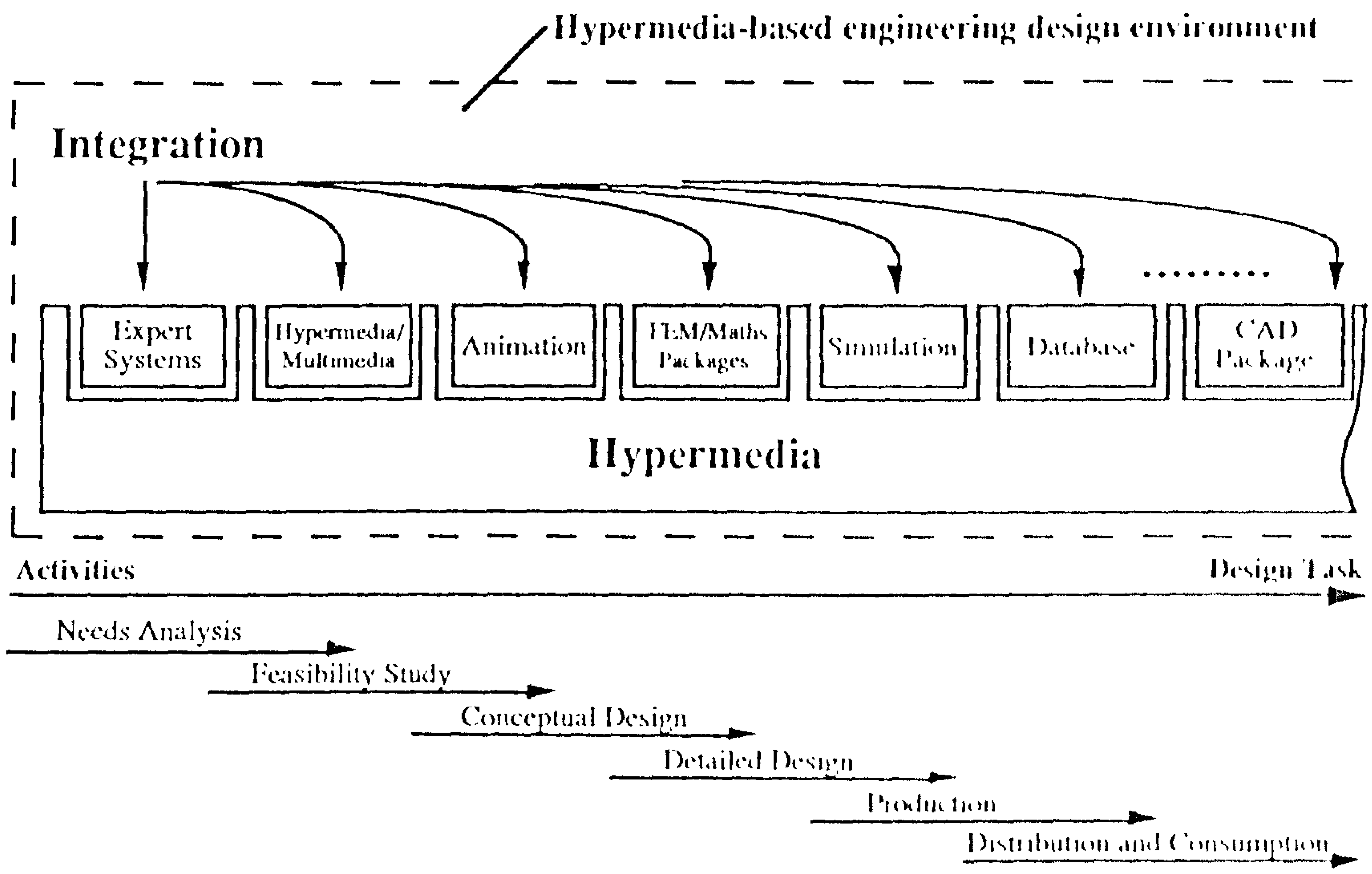


Figure 9.6 HyperCAD structure

design environment. Although each individual aid is used to support different design decisions for different design phases, all aids are interfaced and managed by hypermedia in an organic and associative way with particular reference to the design activities. For example, in the needs analysis phase, the hypermedia/ multimedia and the expert system shell will be used to collect and analyse design information. At the conceptual design phase, animation and computing packages will be integrated and used to generate design ideas and concepts, to establish design function structures, and search for suitable solution principles. At the detailed design phase, FEM, simulation, database, optimisation package, spreadsheet, CAD and customised packages will be integrated and used to determine the arrangement, form, dimensions and surface properties of all the individual parts, and to produce full design documents. At the production phase, CAD/CAM, CAPP (computer aided process planning) and MRP II packages may be integrated to support the production process. Although different design aids are separately used for different decision making, hypermedia will be used as a loading vehicle to link and transport the design ideas and resulting data from one phase to another. The design ideas and data will be continually generated, developed and mediated within the unique macro environment with the development of a product design life cycle. The developing philosophy of HyperCAD is consistent with the methodological requirements implied by the design matrix model.

The development of HyperCAD originated from the need to explore the cognitive aspects of engineering design with particular reference to a computer based design process. Cognitive aspects of computer-based design are a new research area, and are becoming an important part of design theory development[68][120][121][122][123].

9.3.2 Implementation

HyperCAD was first implemented on a Macintosh platform. Figure 9.7 shows a screen copy of the HyperCAD system. The system uses the hypermedia tool HyperCard as a central information management tool. Figure 9.8 shows a typical HyperCAD system framework. HyperCard is the kernel which interfaces the following packages:

- ClarisCAD™,
- Excel™,
- Cricket Graph™,
- Mathematica™,
- WordPerfect™,
- LabVIEW™,
- MacroMind Director™,
- Guide™, and

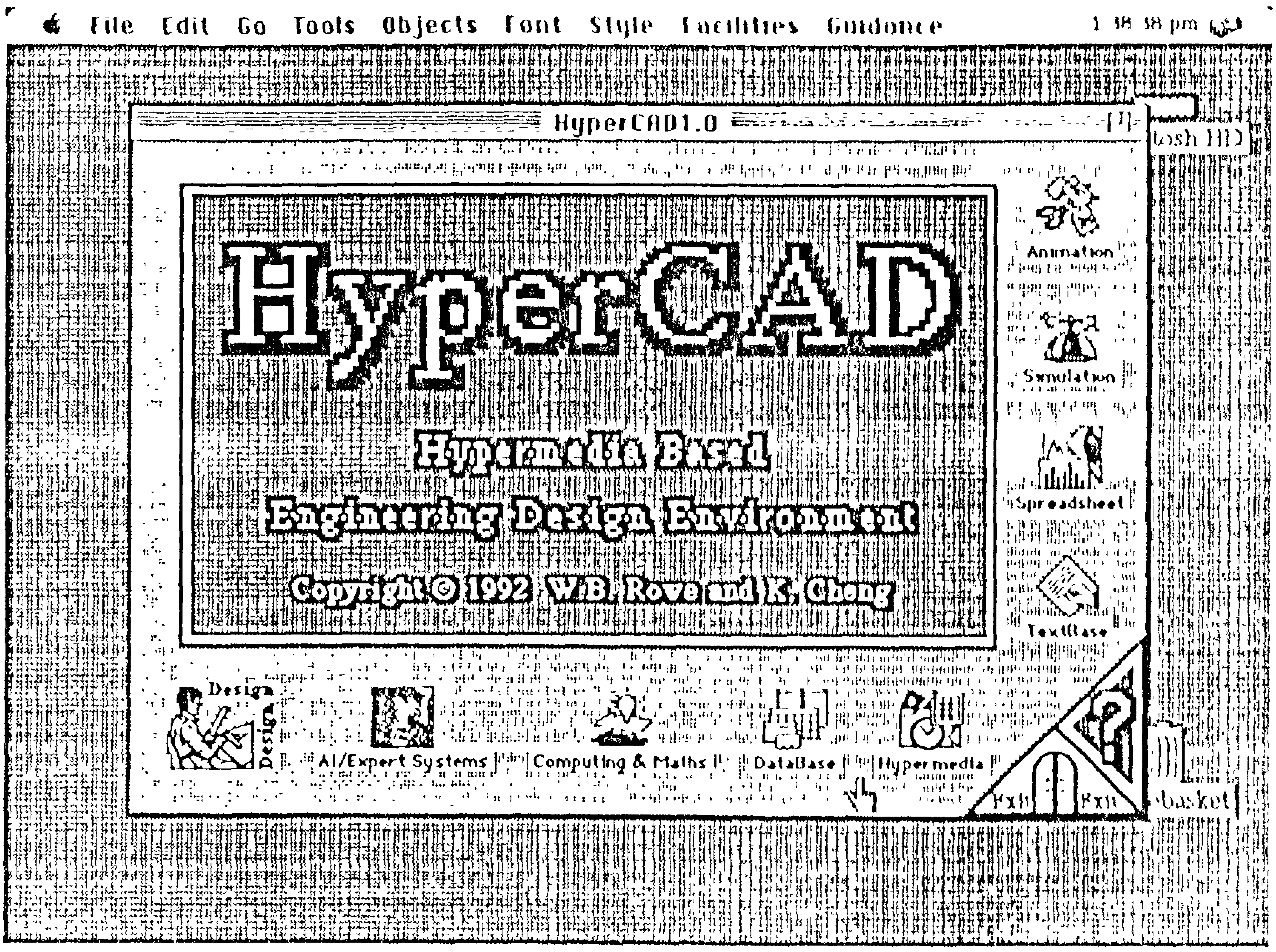


Figure 9.7 The menu card of HyperCAD

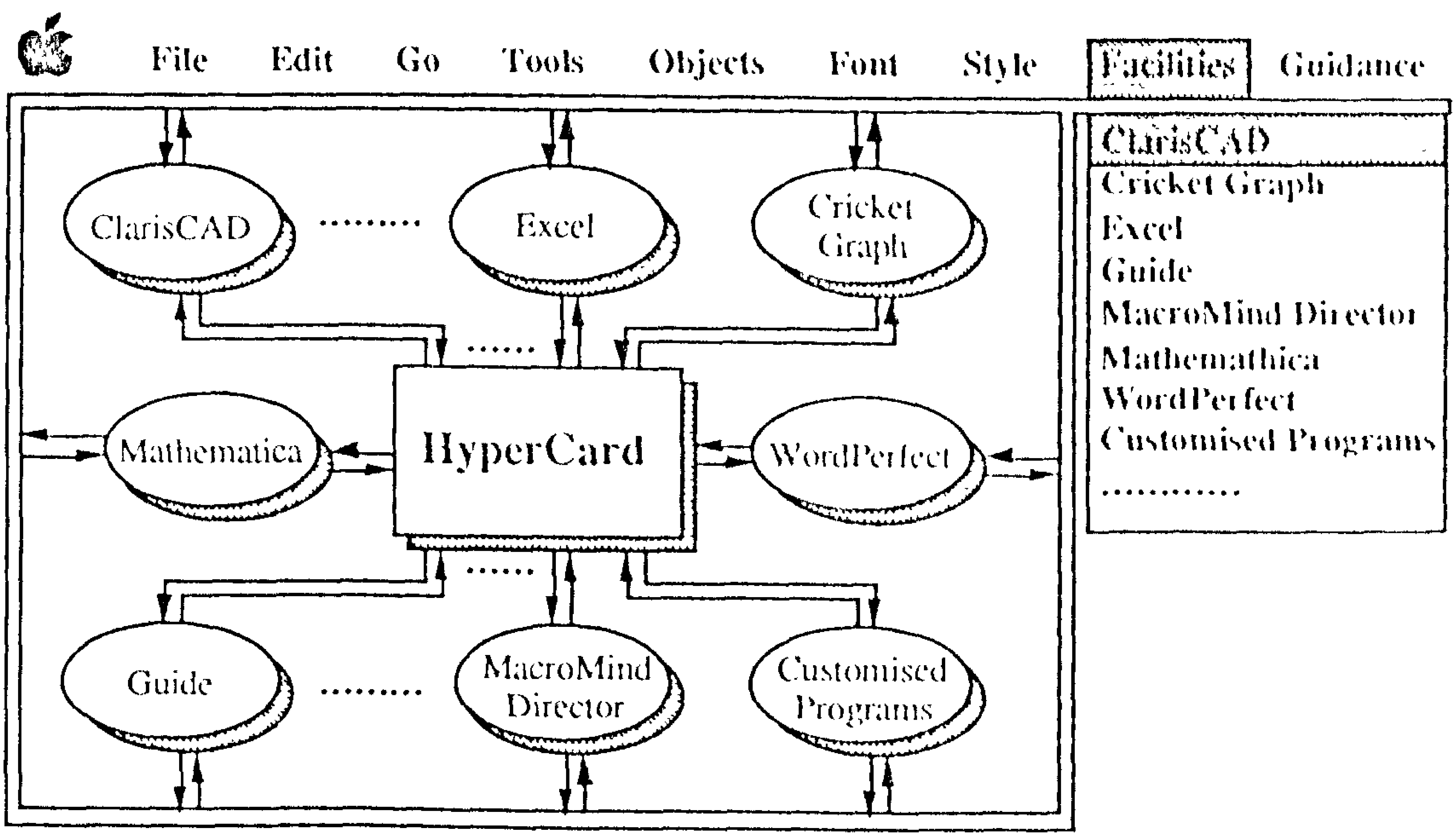


Figure 9.8 HyperCAD framework

- Customised packages, etc.

Each package is used to support a specific area of decision making. HyperCard is used to link the different packages and transport ideas and concepts between the different packages. HyperCard may be used by the designer to store design ideas and concepts, to interface and manage the use of different packages, to maintain the design information as the design progresses through each design phase. The organic integration of all these packages forms a hypermedia-based macro design environment. It is also found that HyperCAD provides a short cut process to integrate many commercial packages. The advantage of integrating commercial packages through HyperCAD sidesteps much of the laborious programming process even though customised programmes are inevitably needed by the designer in the use of HyperCAD to solve particular design problems.

In the HyperCAD environment, hypermedia tools such as HyperCard and Guide have the following functions with which design support can be provided:

- To interface and manage other design support packages.
- To produce multimedia style design information documents.
- To provide intelligent design support by integrating with a knowledge based systems approach.
- To generate animation and virtual reality style simulation.
- To possibly improve the designer's creativity by the associative linkages.
- To support collaboration between designers.

HyperCAD ideas can be implemented on PC, workstation and other platforms. The HyperCAD environment can be computer networked, which is essential and necessary for the collaboration of a design team. Large memory storage using compact disks and the development of powerful personal computers make the application of HyperCAD in engineering design a promising proposal.

9.4 Scenarios using HyperCAD

HyperCAD derives its power from the integration and coordination of various packages. HyperCAD can be used to support a product design process and also the development of a product life cycle. The applications of HyperCAD go far beyond the concepts of traditional CAD. In the following two scenarios, the use of HyperCAD is described in more detail.

(1) Using HyperCAD to support the design process

Figure 9.9 is the screen image of HyperCAD operations in a product design work. The

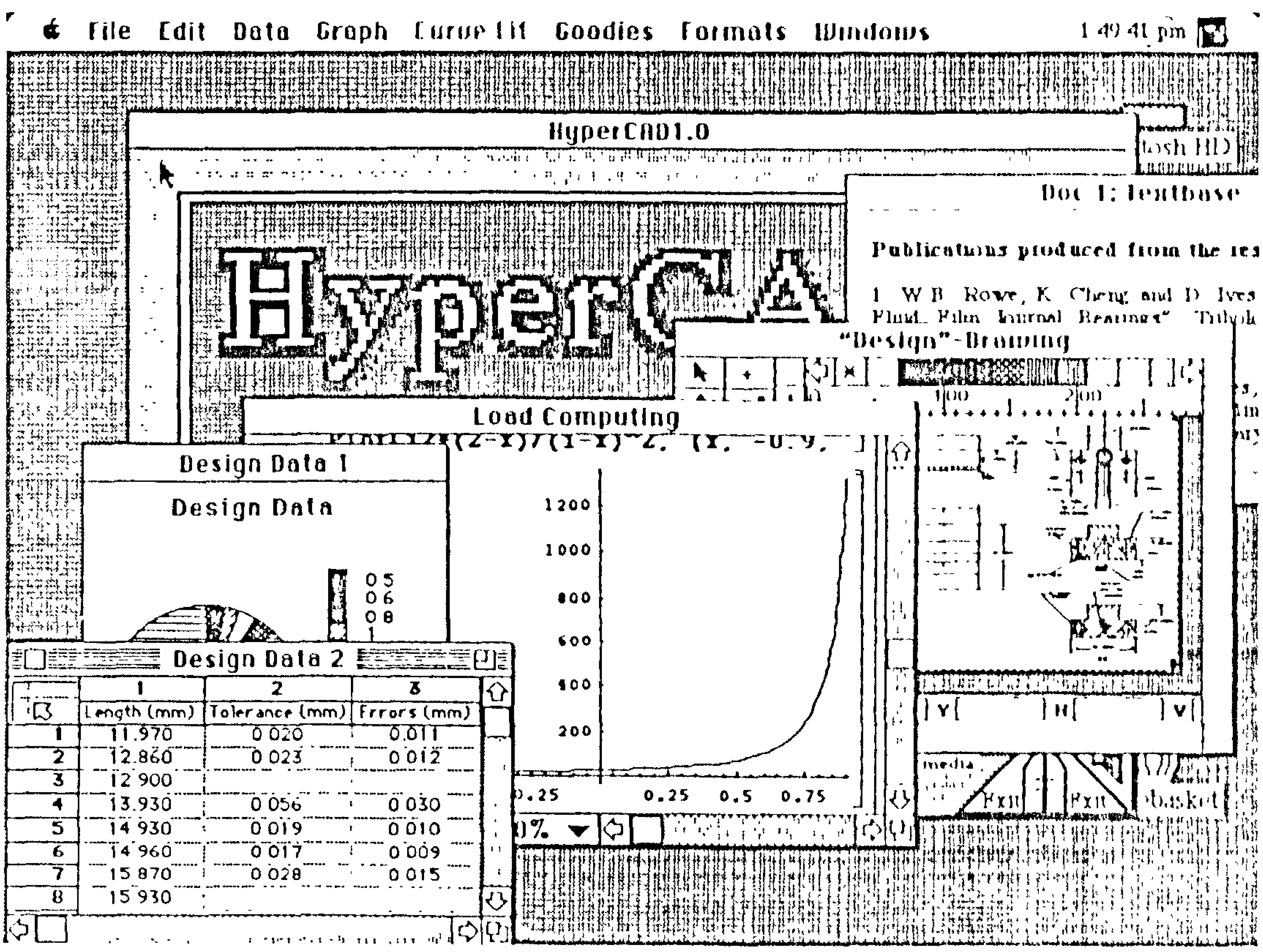


Figure 9.9 A screen image of HyperCAD operations

figure illustrates a scenario in which different design facilities, such as database, spreadsheet, word processing, computing package, and CAD, are accessed in a single hypermedia environment. From the HyperCAD kernel, a designer can constantly access any pre-defined facility. After access, the system can automatically guide the designer back to the kernel. Each facility is used to provide one or more specific decision support aids. The HyperCAD kernel manages the decisions produced by different facilities and coherently mediates the design ideas or data to progress through each design phase.

Because of the limited availability of software packages, the demonstration of HyperCAD only includes a limited number of packages so far. It can be imagined that HyperCAD will be very powerful if a wide variety of design facilities are integrated for the design needs analysis, feasibility study, conceptual design, detailed design, manufacturing, and product marketing management. Figure 9.10 illustrates a future scenario using HyperCAD to support a full design procedure. The scenario also illustrates the trend of further development of HyperCAD.

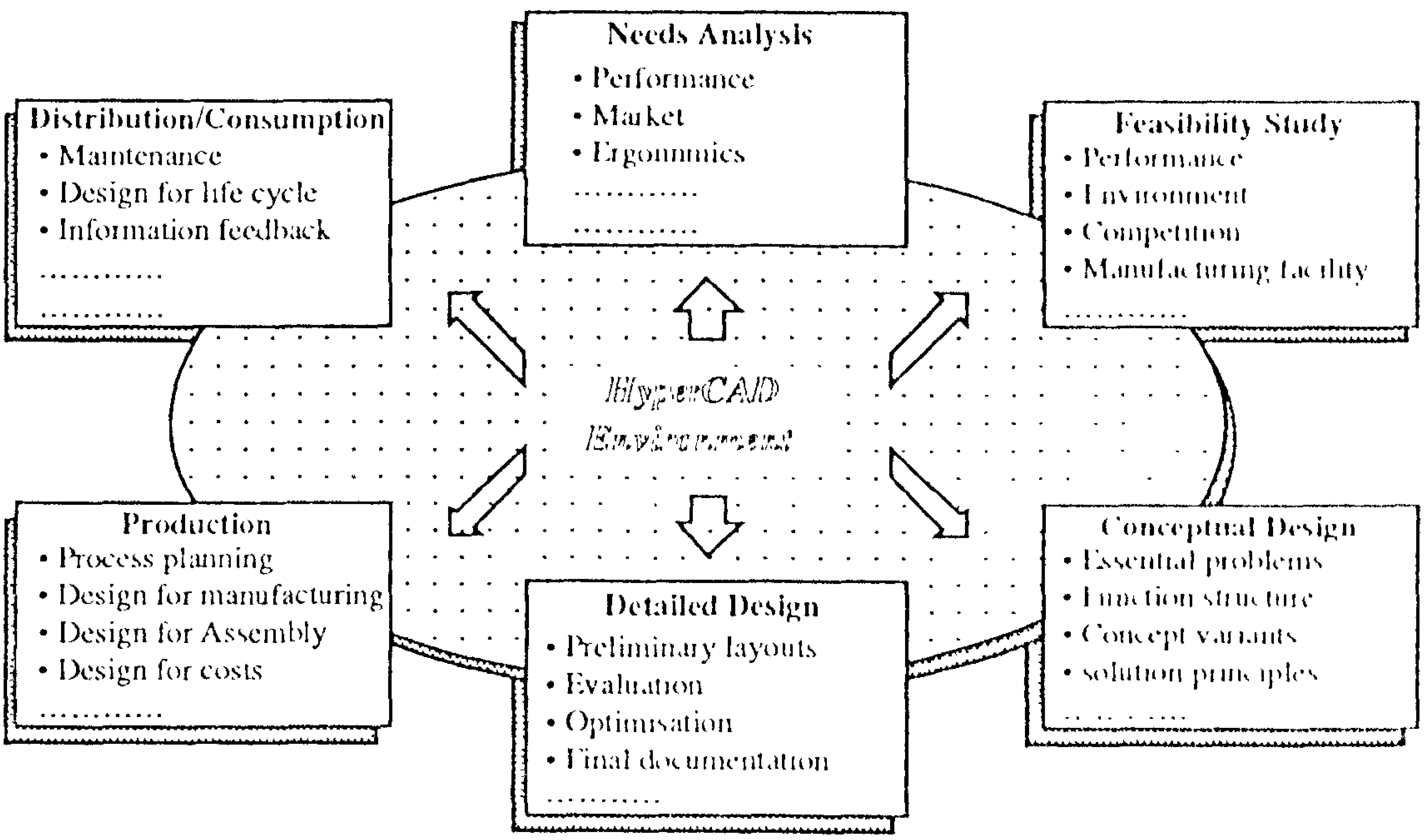


Figure 9.10 A future scenario of HyperCAD used to support the design process

(2) Using HyperCAD in the development of a product life cycle

Figure 9.11 demonstrates a scenario of HyperCAD used in the development of a product life cycle. In this scenario, HyperCAD is used as a networked environment which closely links each stage of a product life cycle as required in concurrent engineering[115][124]. The environment provides a high level of design aid which consists of a wide variety of computer-based support tools for the product development. The support tools which could be included are:

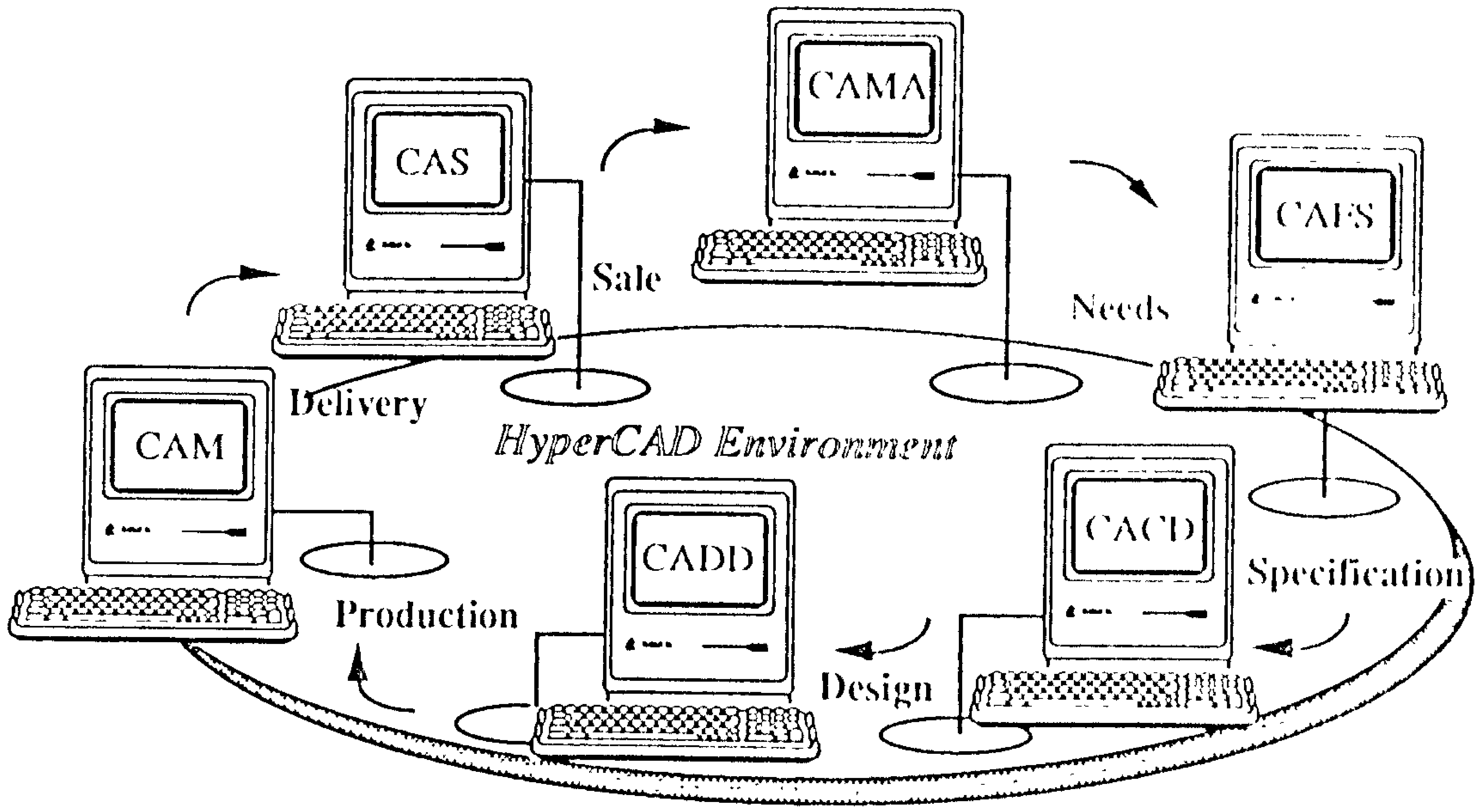


Figure 9.11 A scenario of using HyperCAD in a product developing life cycle

- CAMA - Computer aided market analysis: competition analysis, parametric analysis, patents, and regulations.
- CAFS - Computer aided feasibility study: specification, production techniques, and consumer needs.
- CACD - Computer aided conceptual design: the function structure, suitable solution principles, and concept variants.
- CADD - Computer aided detailed design: components specified, analysis, production documents, and costing.
- CAM - Computer aided manufacture: planning, parts, assembly.
- CAS - Computer aids to selling: stock, re-ordering, availability, transportation, sales, and records.

In this scenario, HyperCAD, as a hypermedia-based environment, manages and coherently mediates the information flow during the product development cycle. In each developing stage, HyperCAD 'calls' in specific facilities to tackle the specific problems. HyperCAD is used as a product development environment rather than as an aid only associated with design. HyperCAD links and integrates market analysis, product specification, design, workshop floor production, delivery, and marketing and provide a visible organisational structure for the product life cycle. HyperCAD is designed to be used as an active partner in the product development team and represents a collaboration of developing effort and knowledge that transcends individual contributions from the developers and computer supports.

9.5 Using HyperCAD for fluid film bearings design

As described in last section, HyperCAD aims to provide a complete support for a product design and further for the product development cycle. A fully developed HyperCAD can be used for the design of fluid film bearings. During the development of HyperCAD, however, the author paid more attention to using HyperCAD for normal engineering design rather than for the design of an objective product such as a fluid film bearing. The author would like to take a fluid film bearing design as an example in the further development of HyperCAD because of the relevance of HyperCAD with the work described in Part I and Part II.

9.6 Conclusions

The potential has been described for the application of a hypermedia based integration environment for the process of design. The development of HyperCAD arises from the requirements of future product design and development. A system of this nature has potential to serve the larger design community and industry. However, the prototype version of HyperCAD is still far from meeting the requirements of practical applications. Great efforts need to be made to cope with the data communication between different facilities, simultaneously sharing data, downstream flow of design idea and concepts, the integration of AI with hypermedia, and other problems in the further development. The author believes, with the development of powerful PCs, networks, and hypermedia technology, the HyperCAD philosophy can be implemented and applied in industry.

Chapter 10 Development of a prototype hypermedia-based system for education in mechanical engineering - HyperCAL

10.1 Introduction

It has been suggested that there are three technologies, hypermedia, simulation and artificial intelligence which will enrich education in the 21st century[125]. The potential of hypermedia in education is increasingly being recognised and explored by educationalists from many higher education disciplines including literature studies[126][127], engineering and technology[128]~[134], natural science [135]~[137], and medicine[138]~[139]. The references cited above represent a small proportion of the relevant publications[140]. Application of hypermedia for use in education has mainly focused on knowledge presentation through text, graphics, video and audio. However, animation, simulation and computing are also expected to be useful in engineering education. The issues associated with the development of hypermedia based engineering education systems need to be studied and formulated.

The main purpose of this chapter is to explore the educational advantages of a hypermedia based system through a computer assisted learning (CAL) environment for engineering application. A prototype system, 'HyperCAL', is described, and development issues discussed with particular reference to animation and simulation techniques.

Computer assisted learning techniques are required in the development of any engineering design package[141]. Including CAL is a trend in the development of a computer aided design system. This is a reason to undertake the investigation of CAL. The further study is consistent with the aims of the thesis and the development of the systems described. The application of CAL to the subject of control engineering is described in greater detail as this was a requirement of the author's bursary. However the principles are equally applicable to CAL for fluid film bearings and further work is planned in this area.

10.2 Hypermedia and learning

10.2.1 Theoretical aspects

There are many concepts of learning. Paradigms of learning include cognitive processing, information processing, behavioural conditioning, cybernetics, and others[142]~[144]. For the purpose of designing CAL systems, learning is usually thought of in terms of learning outcomes. The following three learning processes appear to be particular appropriate for the use of hypermedia techniques[145]:

- Information seeking,
- Knowledge acquisition,
- Problem solving.

(a) Information seeking

Information seeking is an important step in any learning process to satisfy information needs. Seeking information is essential prior to answering a question, making a decision, solving a problem, or comprehending. Information about any domain of knowledge is stored in a variety of forms in many places and organised in different ways. When seeking information, most learners are concerned about information accuracy, understandability and access time. Information seeking is a fundamental learning activity precursive to many others.

Hypermedia has a distinct advantage for information seeking. The advantage is the ability to integrate a large amount of information in alternative representations. Access to information is facilitated by the associative organisation of the information in multimedia, which resembles the associative structure of human memory[146]. Hypermedia is capable of providing different organisational structures for libraries of information, thereby providing access to information in ways that more closely resemble the information seeking behaviour and needs of learners.

(b) Knowledge acquisition

Learning may be viewed as the conceptualisation and reorganisation of knowledge structures[145]. Knowledge structures refer to the organisation of ideas in semantic memory. Ideas are referred to as 'schema'. A schema for an object, event, or idea is comprised of a set of attributes. Attributes are the associations that an individual forms around an idea. These schemata are arranged in a network of interrelated concepts known as a semantic network. Schemata in a semantic network are linked together by attributes or associations. These interconnections enable learners to combine ideas, infer, extrapolate or otherwise reason from them. As described in section 3.3, hypermedia has advantages for knowledge presentation through its links and nodes structural networks. The networks describe what a learner needs to know and provide the foundation for learning new ideas by expanding the learner's semantic networks. This provide a rich conceptual model of learning. Learning, results from the interactive processes of accretion, restructuring and tuning as the learner browses through the networks.

(c) Problem solving

From an information processing perspective, problem solving starts with a problem, which includes a goal state, a starting state, and solution paths to reaching the goal. Generally speaking, problem solving entails the three stages of problem representation, the knowledge transfer and evaluation. Regardless of the nature of the problem, the problem solver first has to represent the problem in a meaningful way. The problem must be stated in terms that the solver understands. The problem representation is the most important stage to the problem solving process. Hypermedia can be used to represent the problem through its nodes and links. By browsing through the representation, a learner will activate relevant knowledge. The knowledge is then applied to the problem as possible solutions. Hypermedia facilitates knowledge transfer process by its link-node and collaborative nature which may provide support for brainstorming, means-ends analysis and analogical reasoning. During a solution evaluation, if a solution does not meet the goal state, the knowledge retrieval process will be reactivated in search of alternative solutions. The collaborative nature of hypermedia may have the potential to facilitate the evaluation process.

McAleese[147], Duchastel[148] and Jacobs[149] investigated the learning ability provided by hypermedia. It was verified that hypermedia provides the possibility of learning knowledge while navigating through hypermedia networks. The work of McAleese, Duchastel and Jacobs provides a basis on which the hypermedia based CAL system was developed.

10.2.2 Potential for engineering education

As shown in Figure 10.1, there are five traditional types of teaching and learning

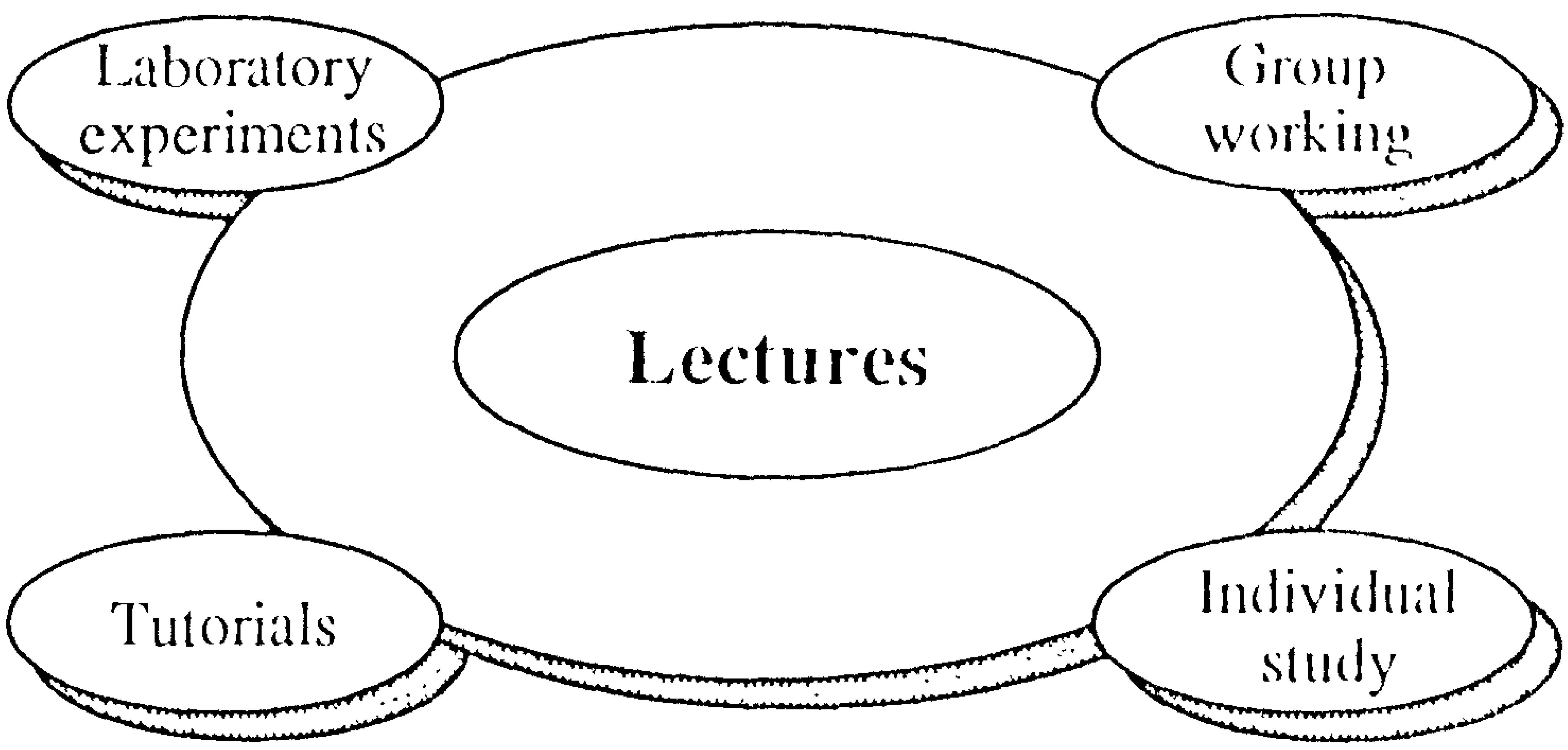


Figure 10.1 Teaching-learning activity components in engineering education

activities in engineering education. These activities are lectures, laboratory experiments, tutorials, group working and individual study. Lectures are usually regarded as the main activity with enhancement provided by other activities. However, the traditional viewpoint of engineering lecturers is currently challenged in engineering education. The situation is being changed for the following reasons[150][151]:

- Students have little or no engineering background knowledge and experience.
- Staff-student ratio is worsening.
- Increasing numbers of students enter with weak analytical and mathematical abilities.
- Emphasis on the 'knowledge' content of subjects rather than on the development of skills and deep understanding is recognised as inadequate.

- Staff have less time to deliver lessons.
- Fewer hours are available for student contact.

Use of hypermedia technology may be an appropriate approach to address the problems described. From an information technology view point, hypermedia has the following features required for CAL[133]:

- Hypermedia is a technique for building a knowledge bank containing a very large amount of knowledge in a particular domain. The organisation is facilitated by the relational linking characteristics.
- Hypermedia allows a learner to quickly find and browse information relevant to a learning objective.
- Hypermedia can aid in the discovery of new ideas or relational information by indicating links to information that might not have been originally sought.
- Hypermedia allows convenient navigation of a learning system. This can be particularly beneficial to learners who may be inexperienced with computer systems.
- Hypermedia can help to clearly define the overall domain of a learning knowledge base by revealing how certain system components or objects are related to each other.
- Hypermedia can support a collaborative learning environment by allowing learners to work on individual pieces of multimedia information which are linked together in a larger hypermedia network.

A computer assisted learning system can be enriched through the provision of a variety of multimedia style materials such as text, graphics, image, animation, simulation, video and audio. Materials for the five teaching and learning activities can be incorporated into one hypermedia-based CAL environment. Therefore, a hypermedia based CAL system has the potential to offer[152]:

- a learning environment in which students are actively involved in the learning process and through which a deeper understanding of the principles, concepts and practice may be achieved.
- a shift from predominantly passive, lecture-centred delivery to active student-centred

learning.

- different learning rates.
- provision for diverse backgrounds by access to wide-based learning materials..
- a way round artificial boundaries between disciplines and subjects.
- a 'safe' environment through animation/simulation modes to explore hazardous or expensive experiment activities.
- more enthusiasm in staff and students through the system-learner interaction. Enthusiasm is a crucial ingredient for successful learning.

Interaction with a hypermedia-based CAL system may result in a better understanding of the material taught because of its flexibility of nonlinear access to information and ability to foster exploration of relevant information in different media. Animation, simulation and computing modes are particularly effective in knowledge representation of engineering objects[153]. Animation, simulation and computing features are fully emphasised in the development of HyperCAL.

10.3 Development of HyperCAL

10.3.1 System framework

Figure 10.2 shows the menu card of the HyperCAL system. As shown on the card, there are nine typical mechanical engineering subjects incorporated into the system. Each subject module can be entered by clicking the subject icon on the menu card or using the system pull-down menu. Figure 10.3 illustrates the basic framework of the system. The system mainly consists of subject modules and three auxiliary modules such as on-line help, trace-map and index. Each module is a stack of a HyperCard structure. New subject modules can be incorporated into the system. The menu card acts as the system master card. All system modules are connected to the menu card. By clicking the 'Liverpool John Moores University' logo on each module card or using the 'Home' item within the 'Go' pull-down menu, a learner can go to the system menu card from any module. By interacting with each subject module, a learner can access and achieve the knowledge included in the module. During the interaction, a learner can use the auxiliary modules such as index, trace-map, and on-line help modules to receive

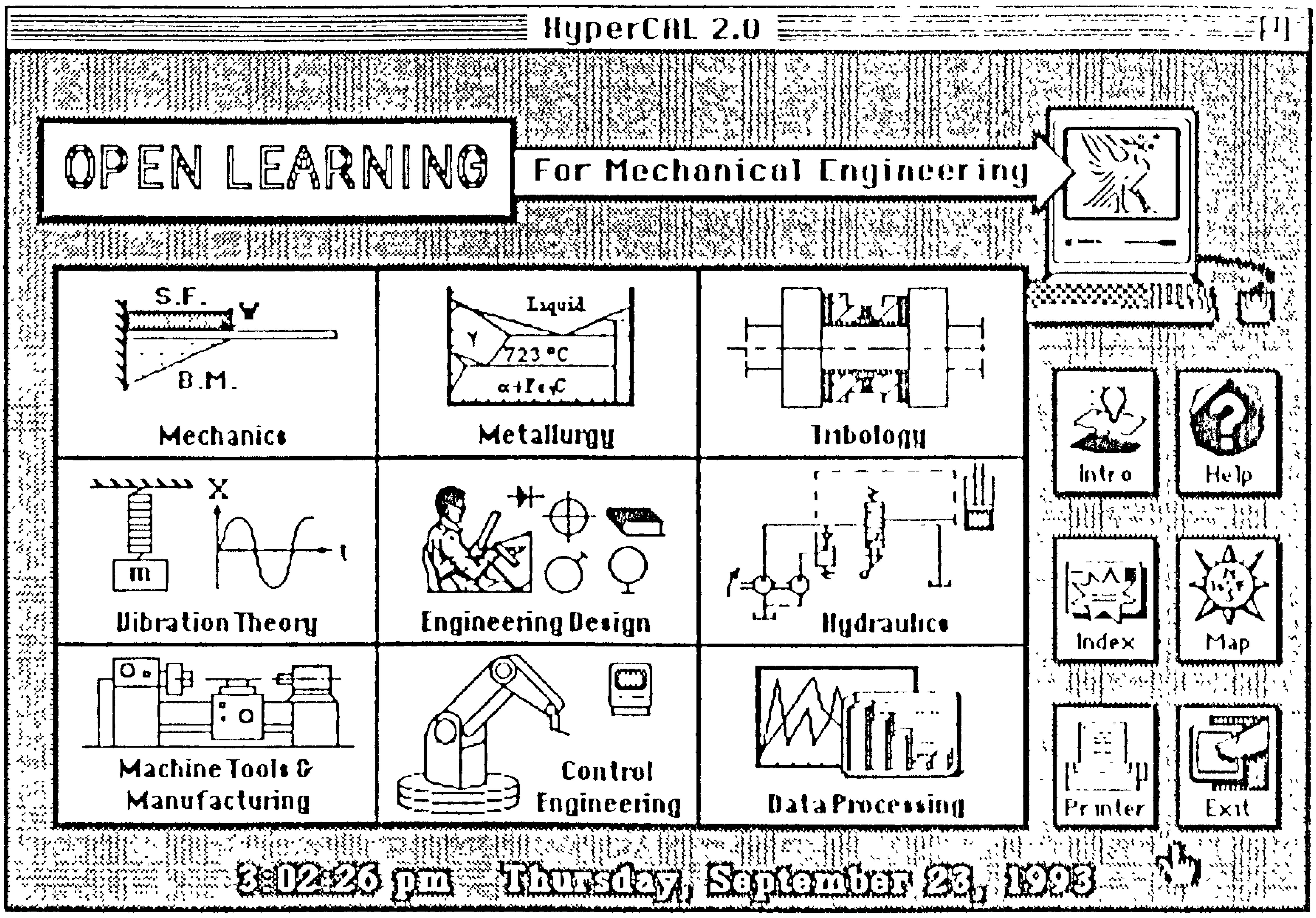


Figure 2 HyperCAL menu card

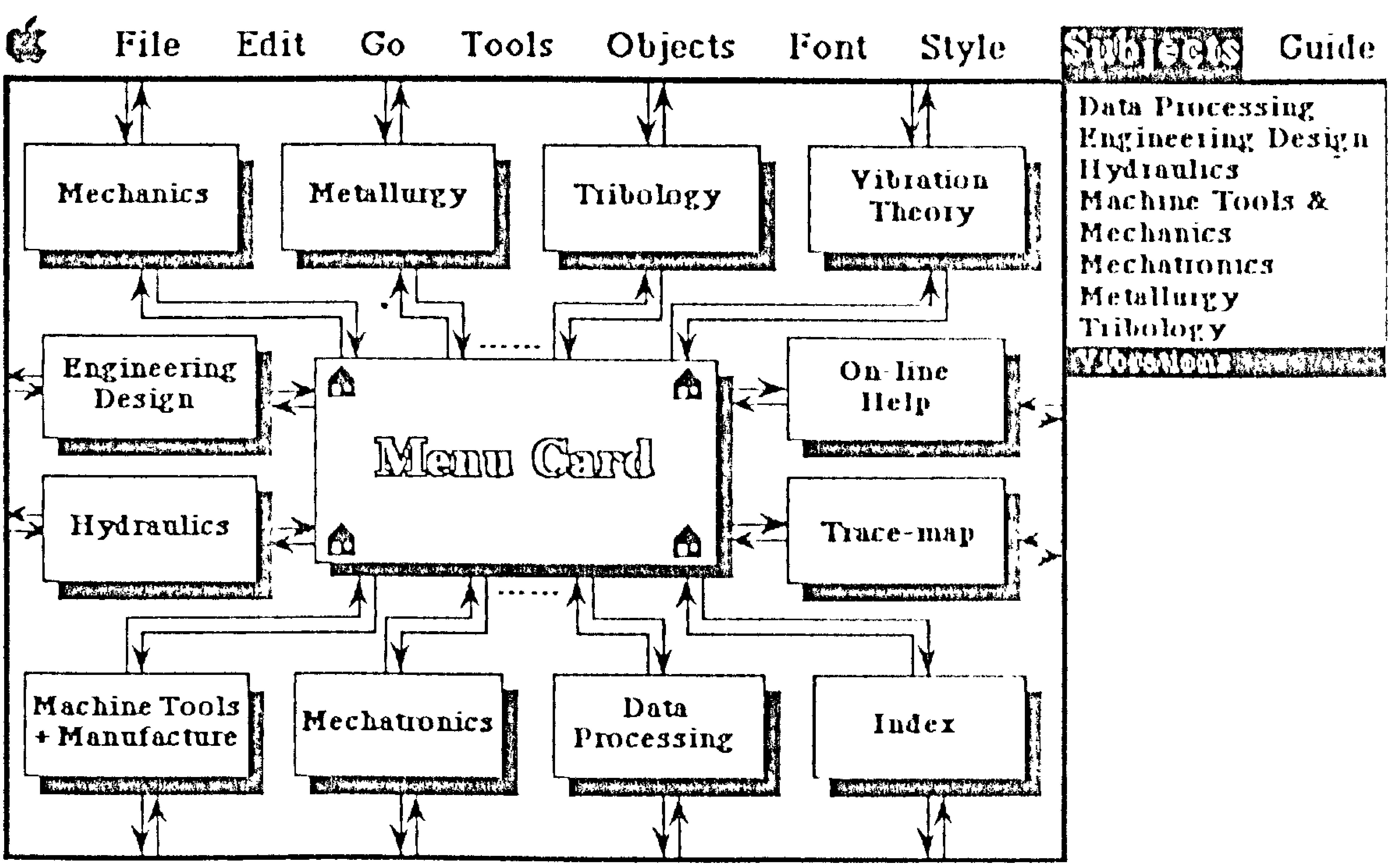


Figure 10.3 The diagram of the system basic framework

assistance in using the system. These auxiliary functions are essential for a hypermedia-based CAL system.

10.3.2 Subject module

As shown in Figure 10.4, each subject module uses text information as a structural

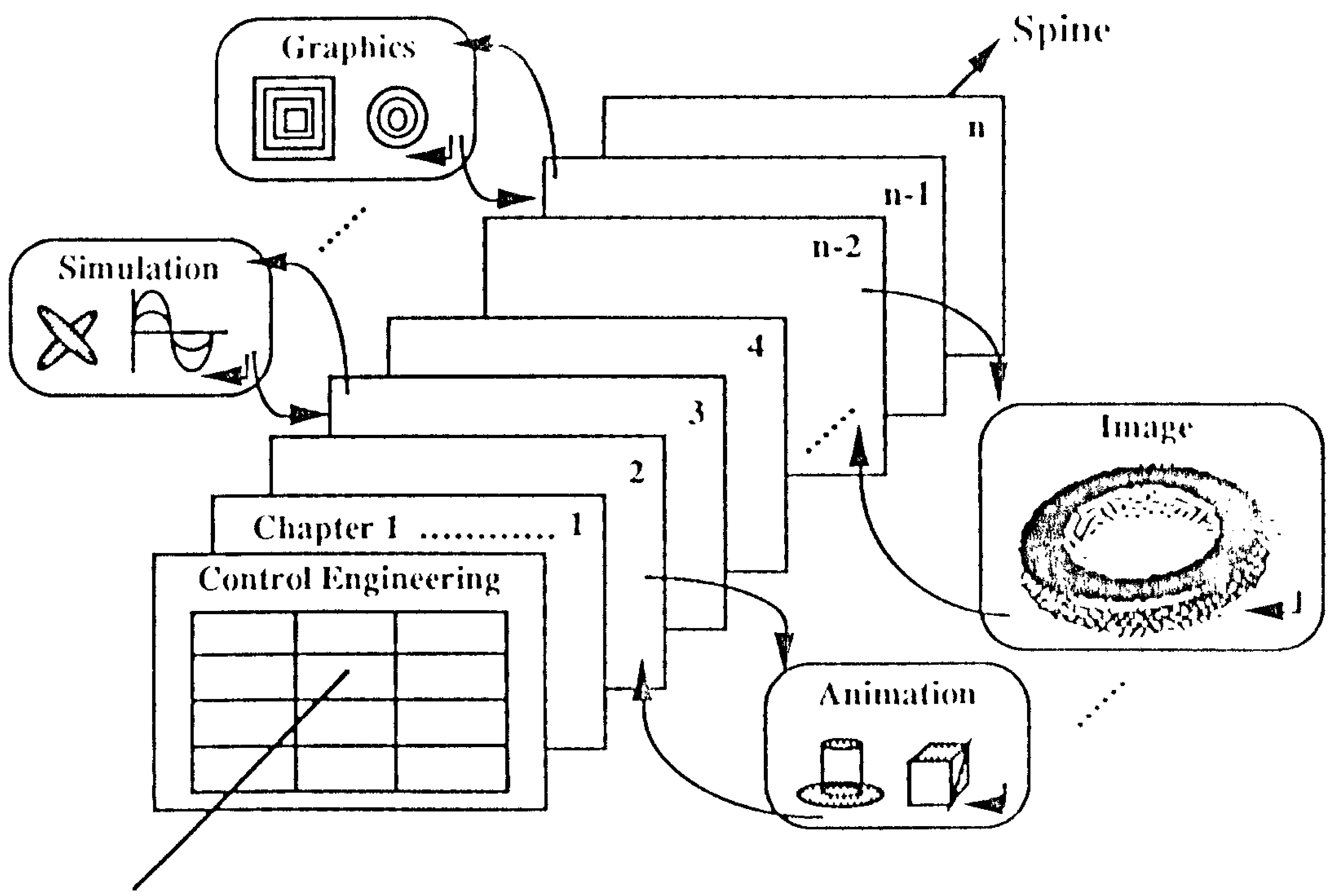
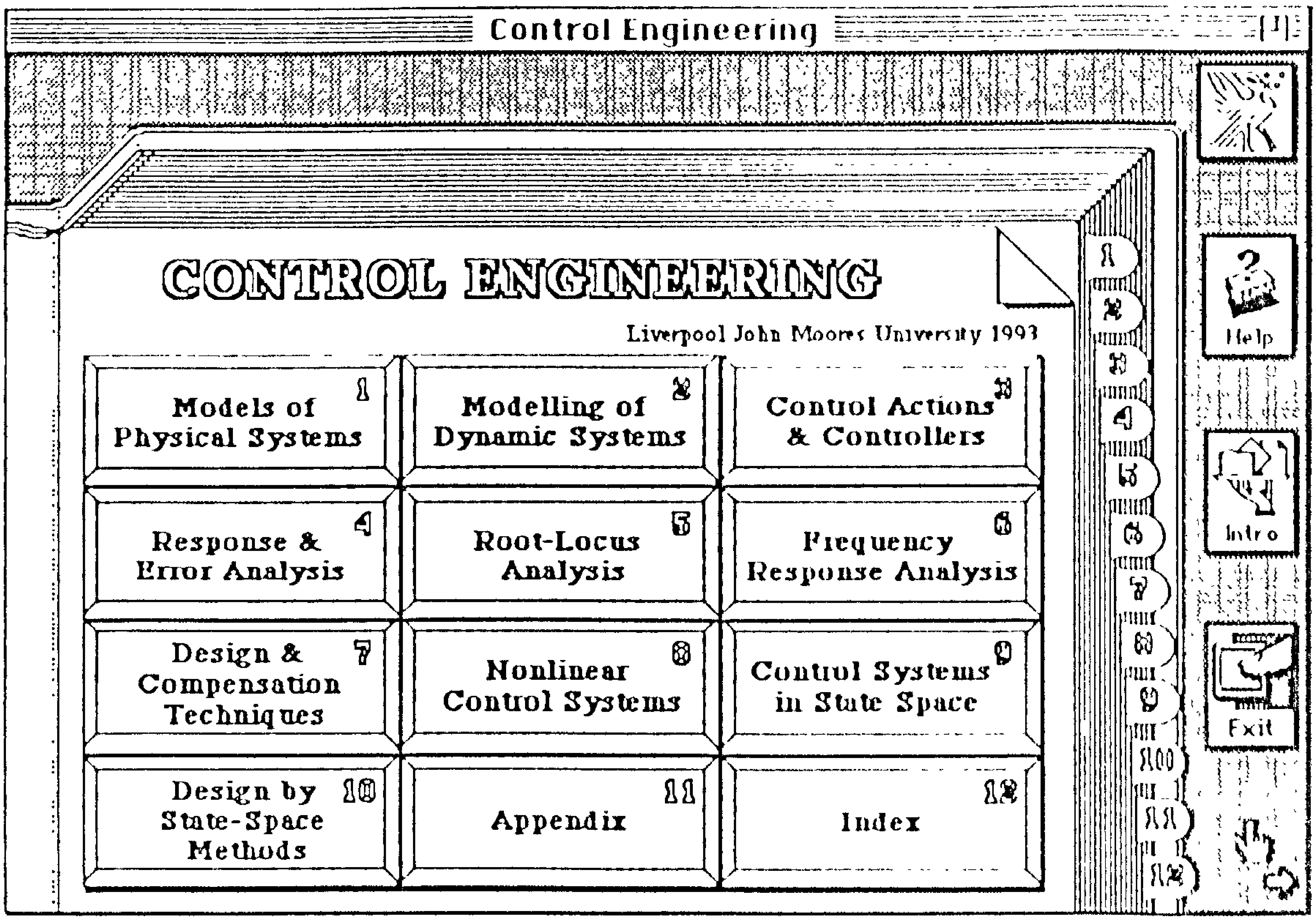
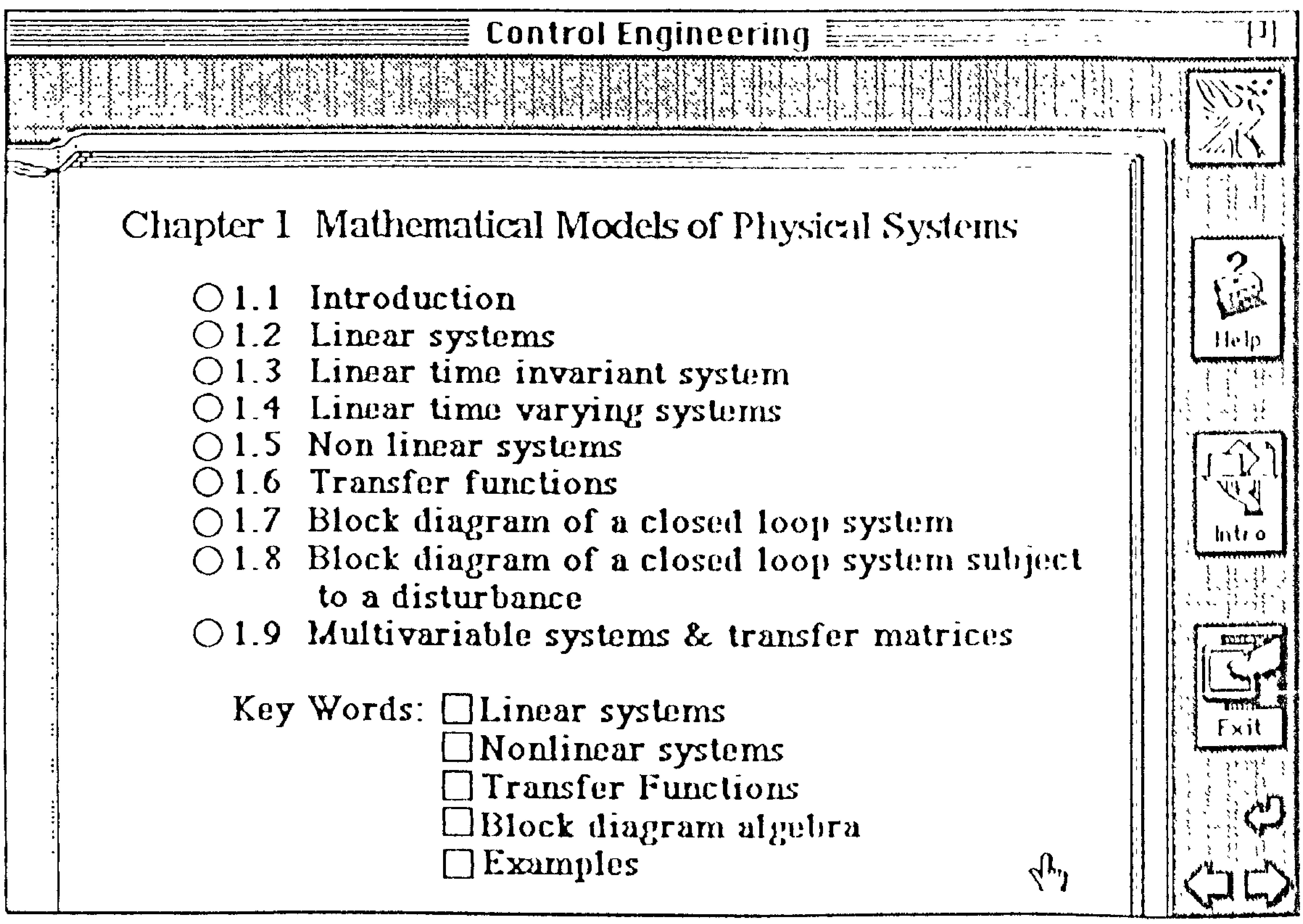


Figure 10.4 A subject module structure

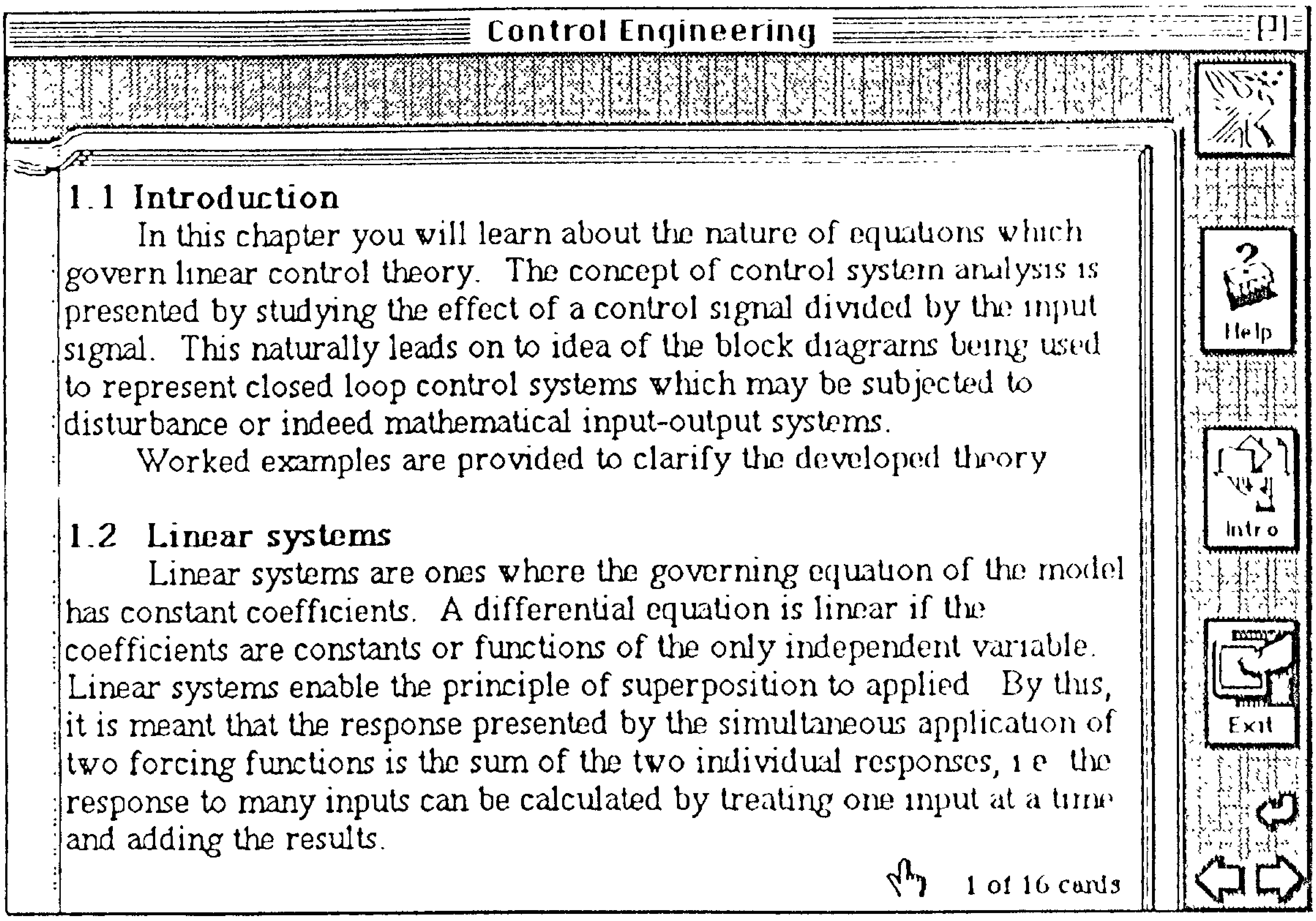
spine. A 'book' paradigm is superimposed on the 'card' paradigm to assist in navigation. The text is divided into chapters and cards which correspond to pages. Other medium information, such as graphics, images, animation and simulation, is added on as required. These added media are authored in hypermedia node link techniques and incorporated with the text information to enhance the knowledge representation and transfer. The text information is based on the lecturers' lecturing notes. Other media, especially, animation and simulation are programmed to provide learners with scope to undertake a deep interactive study. The design of animation and simulation materials are very important but time-consuming. Figure 10.5 illustrates example of cards copied from the control engineering module. This module is based on the structure illustrated in Figure 10.4.

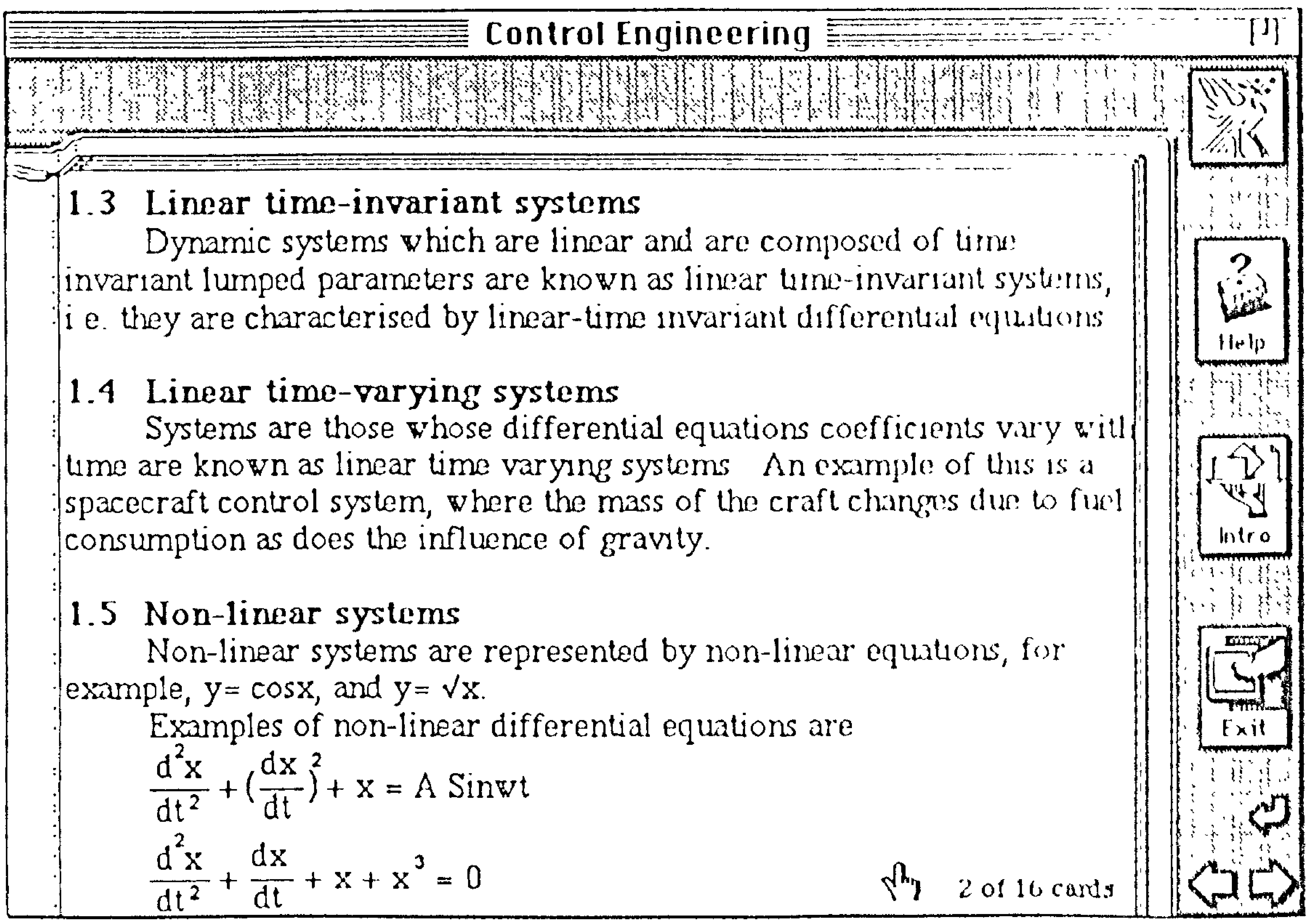


(a)



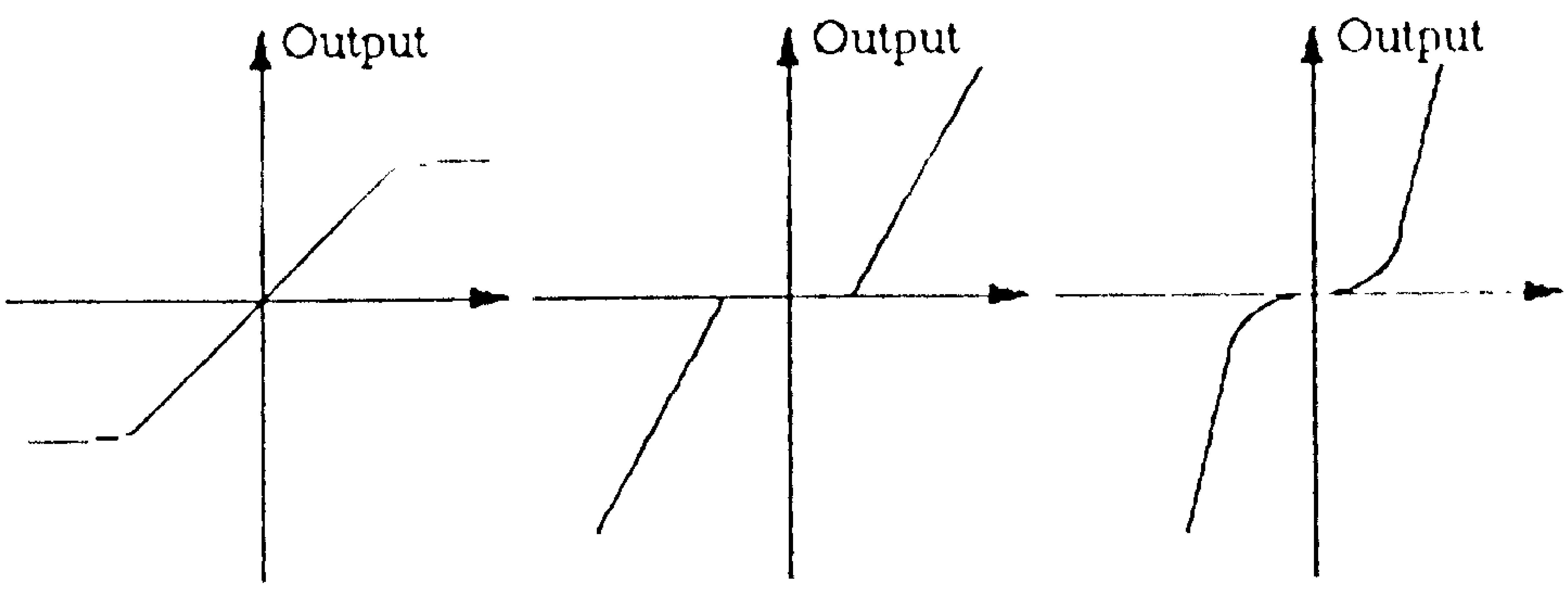
(b)


Control Engineering
1.1 Introduction
In this chapter you will learn about the nature of equations which govern linear control theory. The concept of control system analysis is presented by studying the effect of a control signal divided by the input signal. This naturally leads on to idea of the block diagrams being used to represent closed loop control systems which may be subjected to disturbance or indeed mathematical input-output systems.
Worked examples are provided to clarify the developed theory
1.2 Linear systems
Linear systems are ones where the governing equation of the model has constant coefficients. A differential equation is linear if the coefficients are constants or functions of the only independent variable. Linear systems enable the principle of superposition to applied. By this, it is meant that the response presented by the simultaneous application of two forcing functions is the sum of the two individual responses, i e. the response to many inputs can be calculated by treating one input at a time and adding the results.
1 of 16 cards
Help
Intro
Exit
(c)


Control Engineering
1.3 Linear time-invariant systems
Dynamic systems which are linear and are composed of time invariant lumped parameters are known as linear time-invariant systems, i e. they are characterised by linear-time invariant differential equations
1.4 Linear time-varying systems
Systems are those whose differential equations coefficients vary with time are known as linear time varying systems. An example of this is a spacecraft control system, where the mass of the craft changes due to fuel consumption as does the influence of gravity.
1.5 Non-linear systems
Non-linear systems are represented by non-linear equations, for example, y= cosx, and y= √x.
Examples of non-linear differential equations are
$\frac{d^2x}{dt^2} + (\frac{dx}{dt})^2 + x = A \sin wt$
$\frac{d^2x}{dt^2} + \frac{dx}{dt} + x + x^3 = 0$
2 of 16 cards
Help
Intro
Exit
(d)

Control Engineering

Although many physical systems are represented by linear equations in practice this is rarely the case For example many electromechanical, hydraulic and pneumatic systems involve nonlinear relationships among these variables Figure 1 0 contains characteristic curves for various non linearities.



(a) Saturation (b) Dead zone (c) Square law

Figure 1.0 Non-linearities

3 of 16 cards

(e)

Control Engineering

1.6 Transfer functions

In control theory transfer functions are often used to characterise input-output relationships of Linear Time Invariant Systems

The transfer function of a linear time invariant system is defined as the ratio of the Laplace transform of the output to the Laplace transform of the input.

Consider

$$a_0 y^{(n)} + a_1 y^{(n-1)} + \dots a_{n-1}\dot{y} + a_n y$$

$$= b_0 x^{(m)} + b_1 x^{(m-1)} + \dots b_{m-1}\dot{x} + b_m x \quad (n \geq m) \cdots\cdots \quad \langle 1 \rangle$$

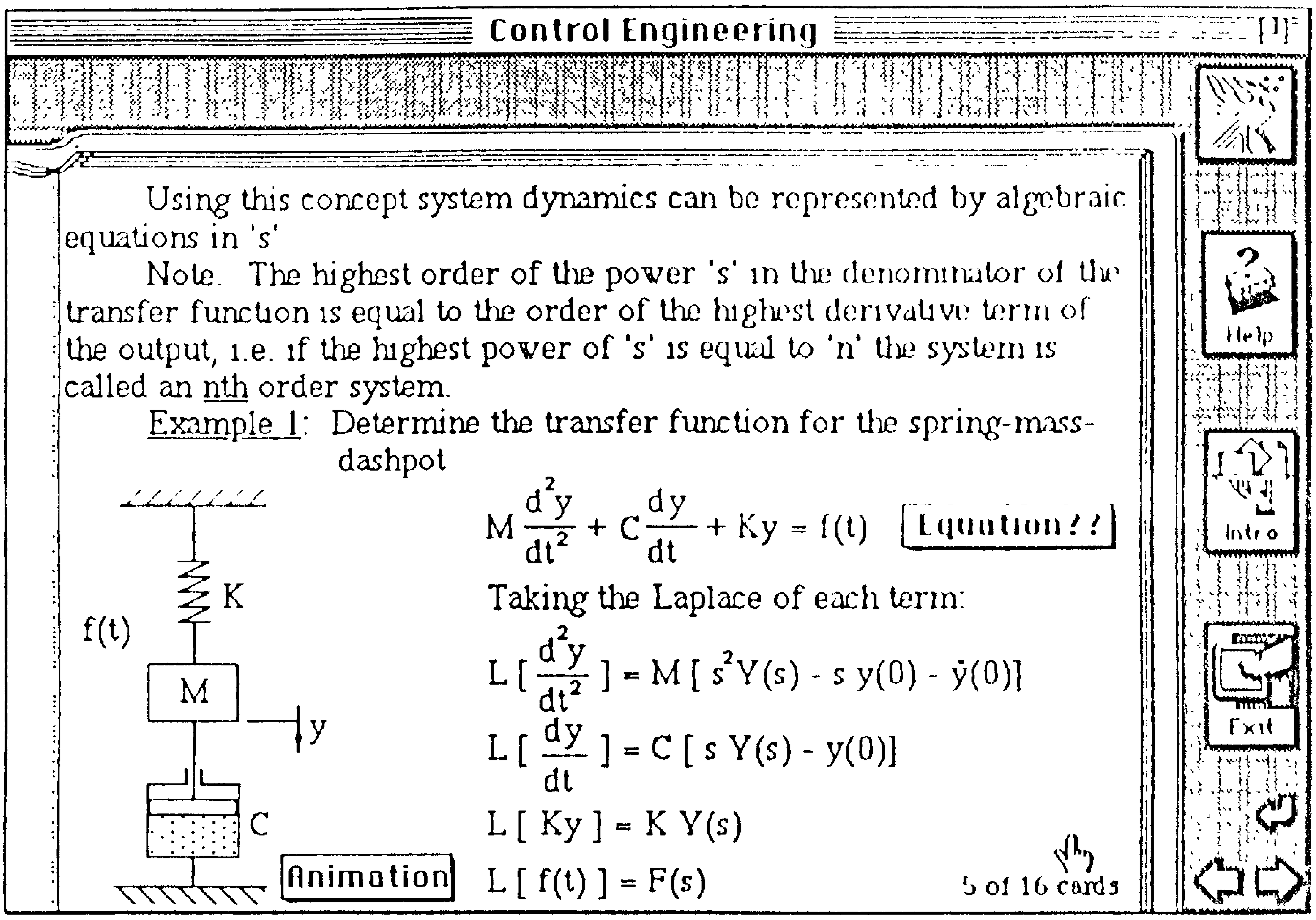
This is a differential equation where y is the output and x is the input. Taking the Laplace transform of equation <1> and assuming that all initial conditions are zero yields the transfer function

Transfer function = G(s) = Y(s)/X(s)

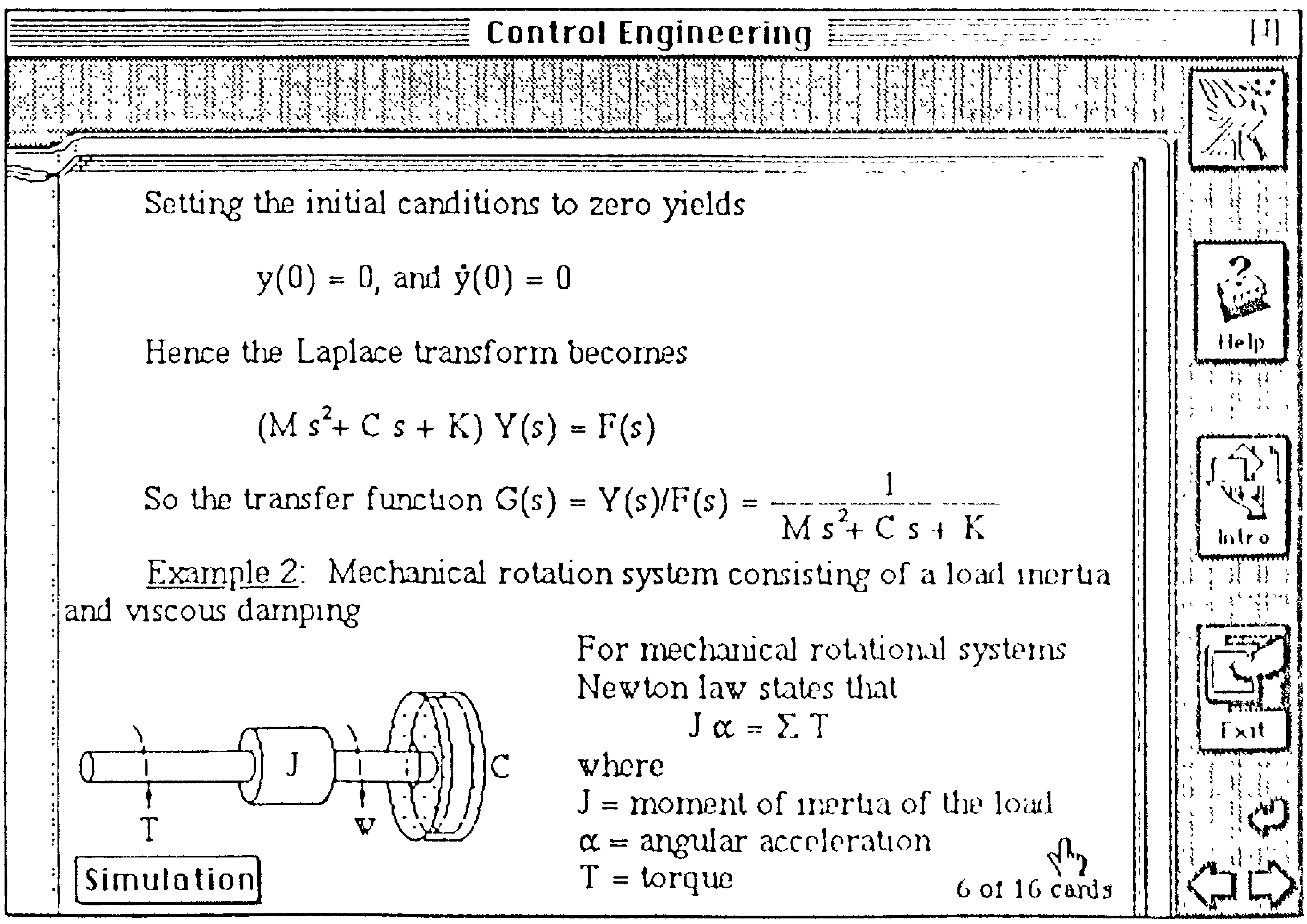
$$= \frac{b_0 s^m + b_1 s^{m-1} + \dots + b_{m-1} s + b_m}{a_0 s^n + a_1 s^{n-1} + \dots + a_{n-1} s + a_n}$$

4 of 16 cards

(f)



(g)

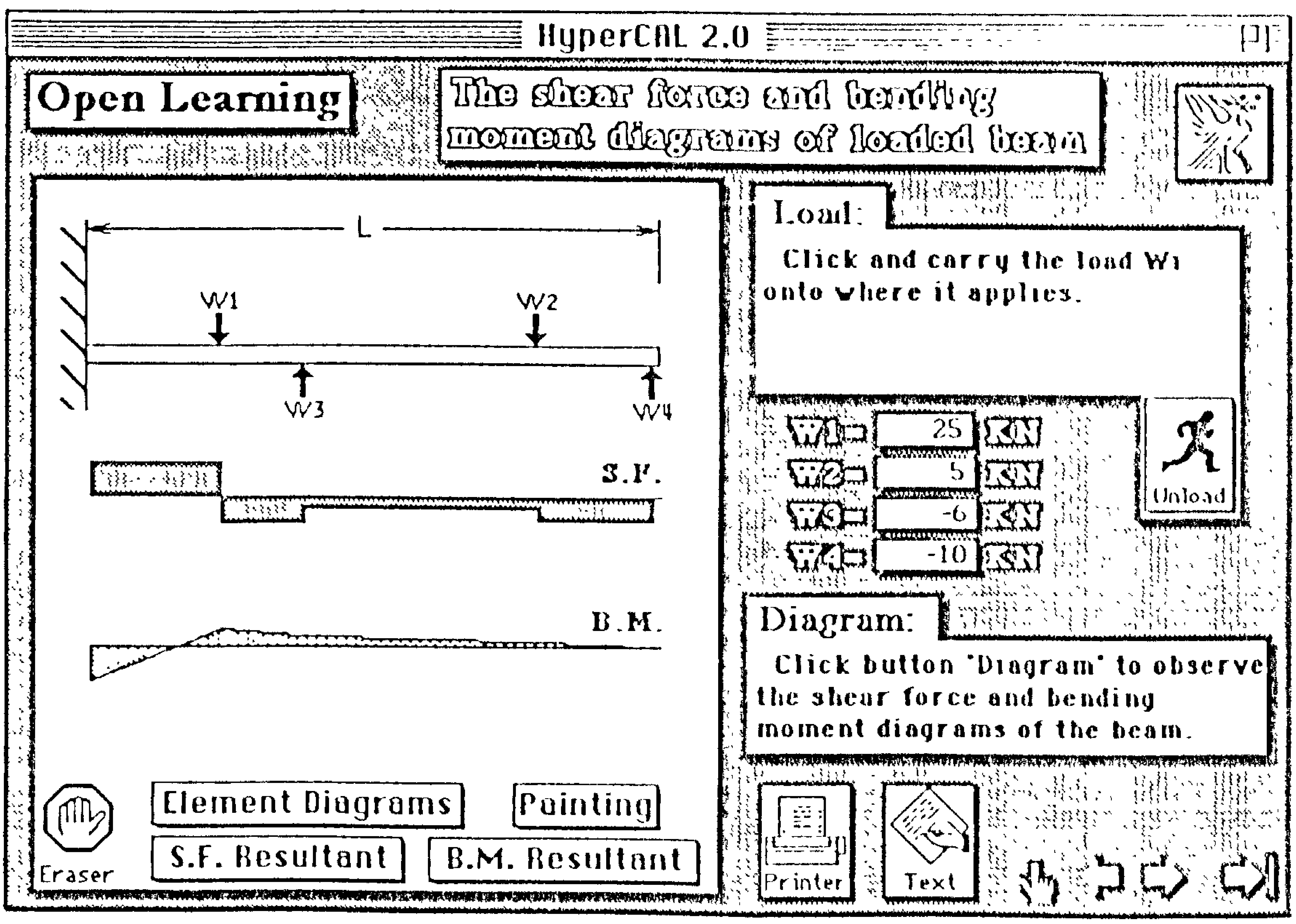


(h)

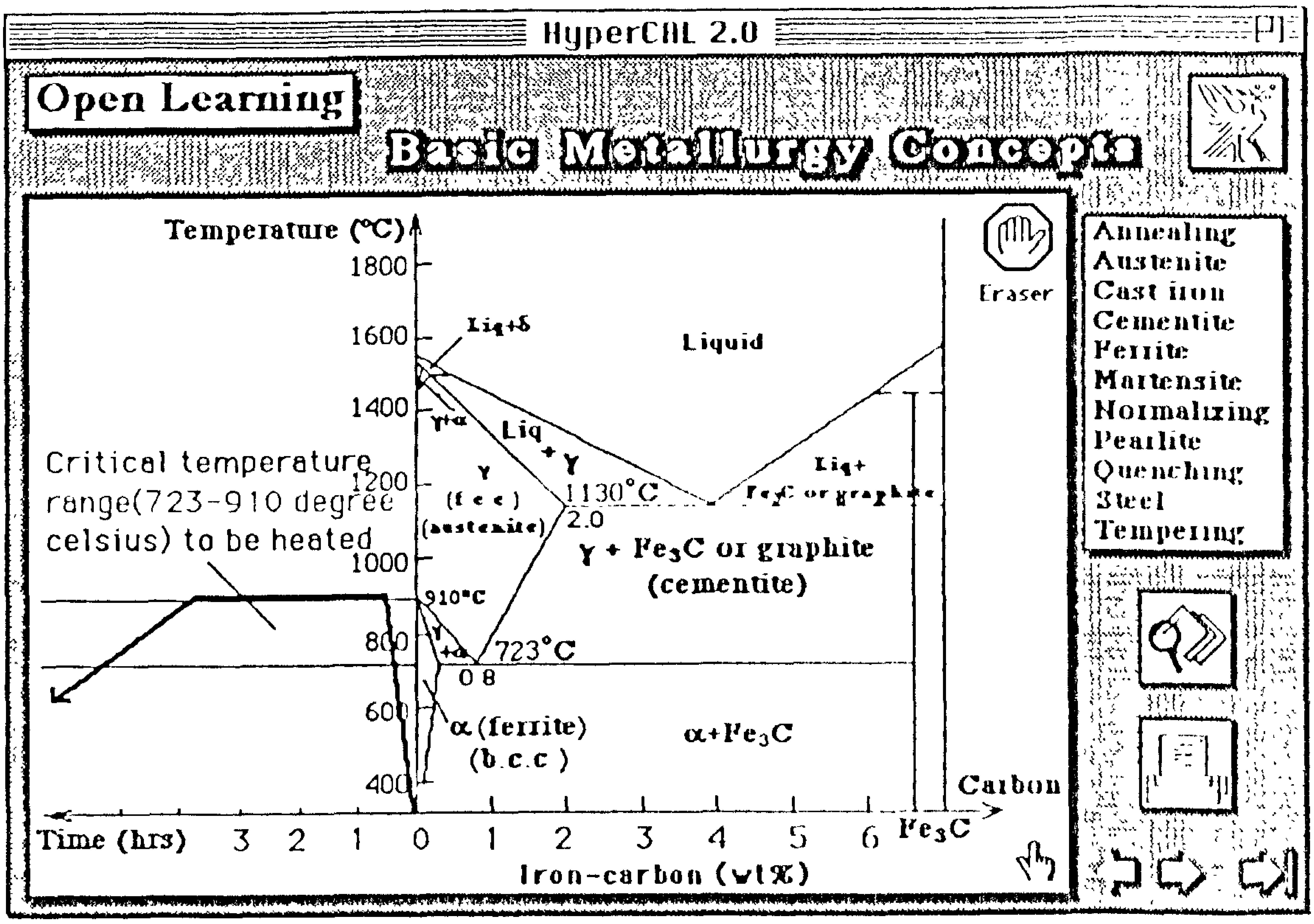
Figure 10.5 Examples of cards from the control engineering module

10.3.3 Implementation

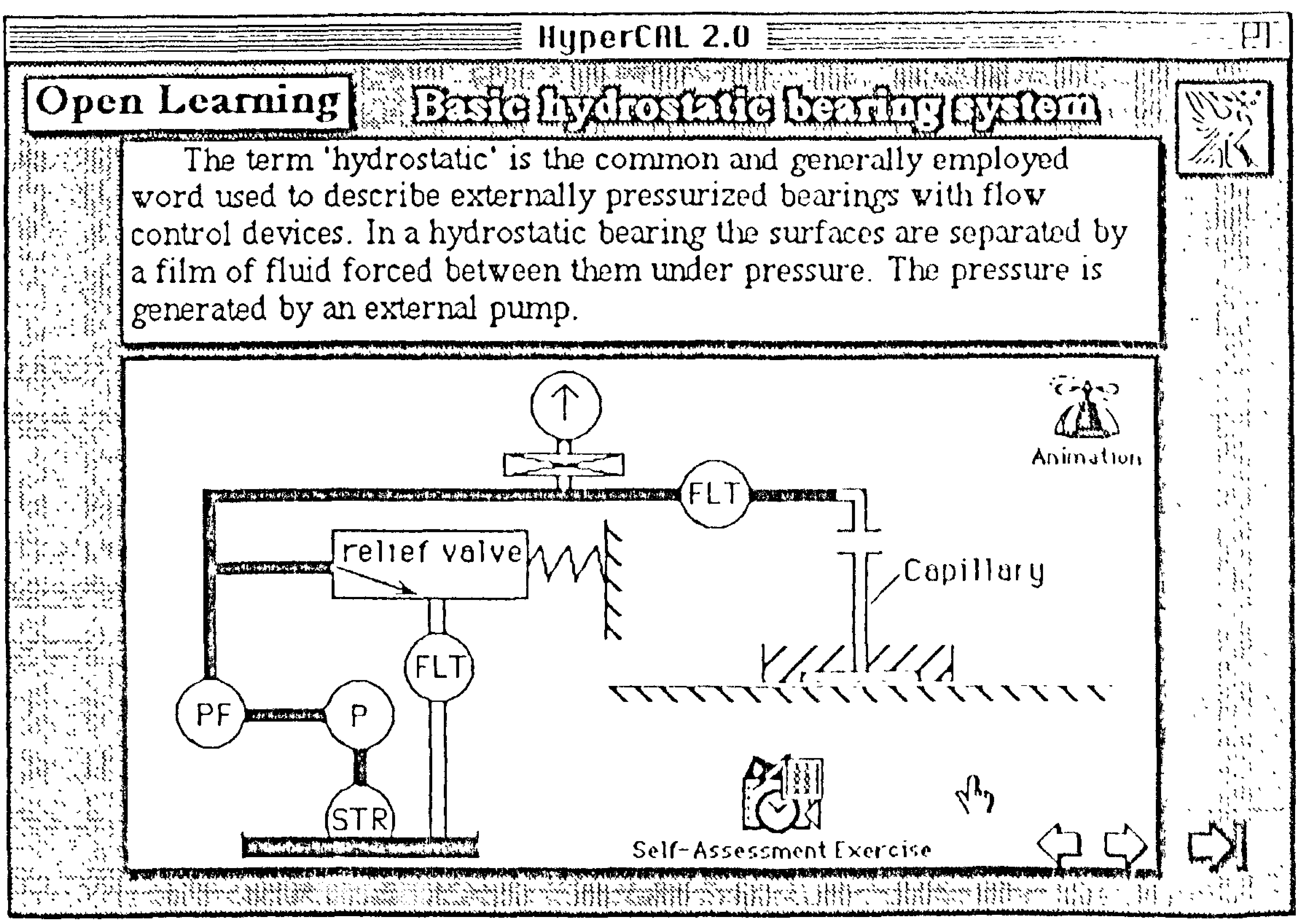
The HyperCAL system was implemented on HyperCard on a Macintosh computer. System pull-down menus were added using Pascal programs which are linked to HyperTalk program operation in XCMD statements. The animation and simulation materials are mainly programmed in HyperTalk and Pascal. The subject materials developed so far have been mainly for the control engineering module. The eight other subject modules contain samples but are far from fully developed. Figure 10.6 illustrates eight cards which are individually copied from these subject modules. All the modules emphasise the animation/simulation based interaction through which the subject knowledge can be explored by a learner. The example demonstrated on each subject card in Figure 10.6 shows the potential and reality of hypermedia technology being used in engineering computer assisted learning. The HyperCAL package requires about 1 MB of memory as designed so far. The system operation needs HyperCard 2.0 and Macintosh System 6.05 or higher.



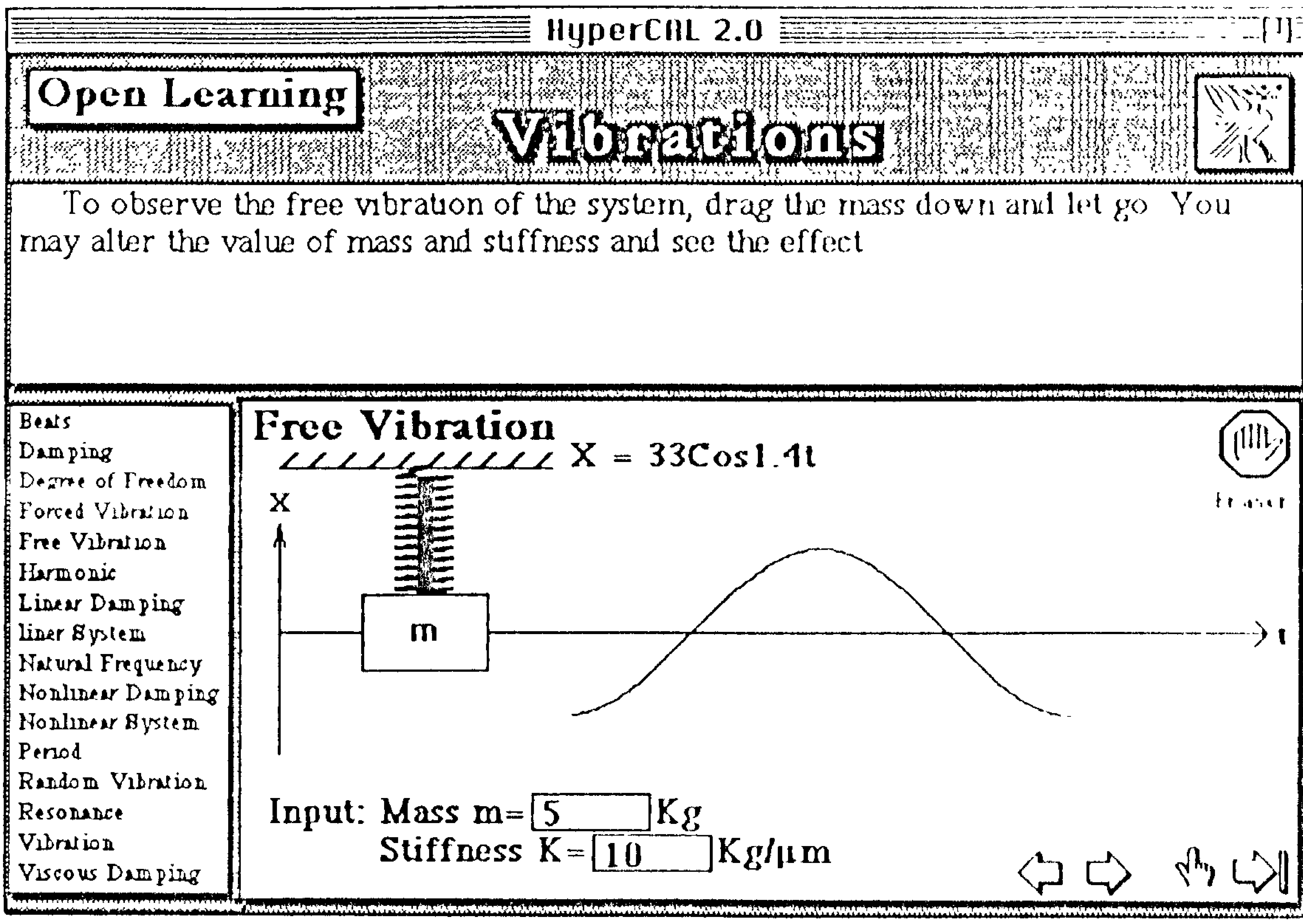
(a) A card copied from the mechanics module



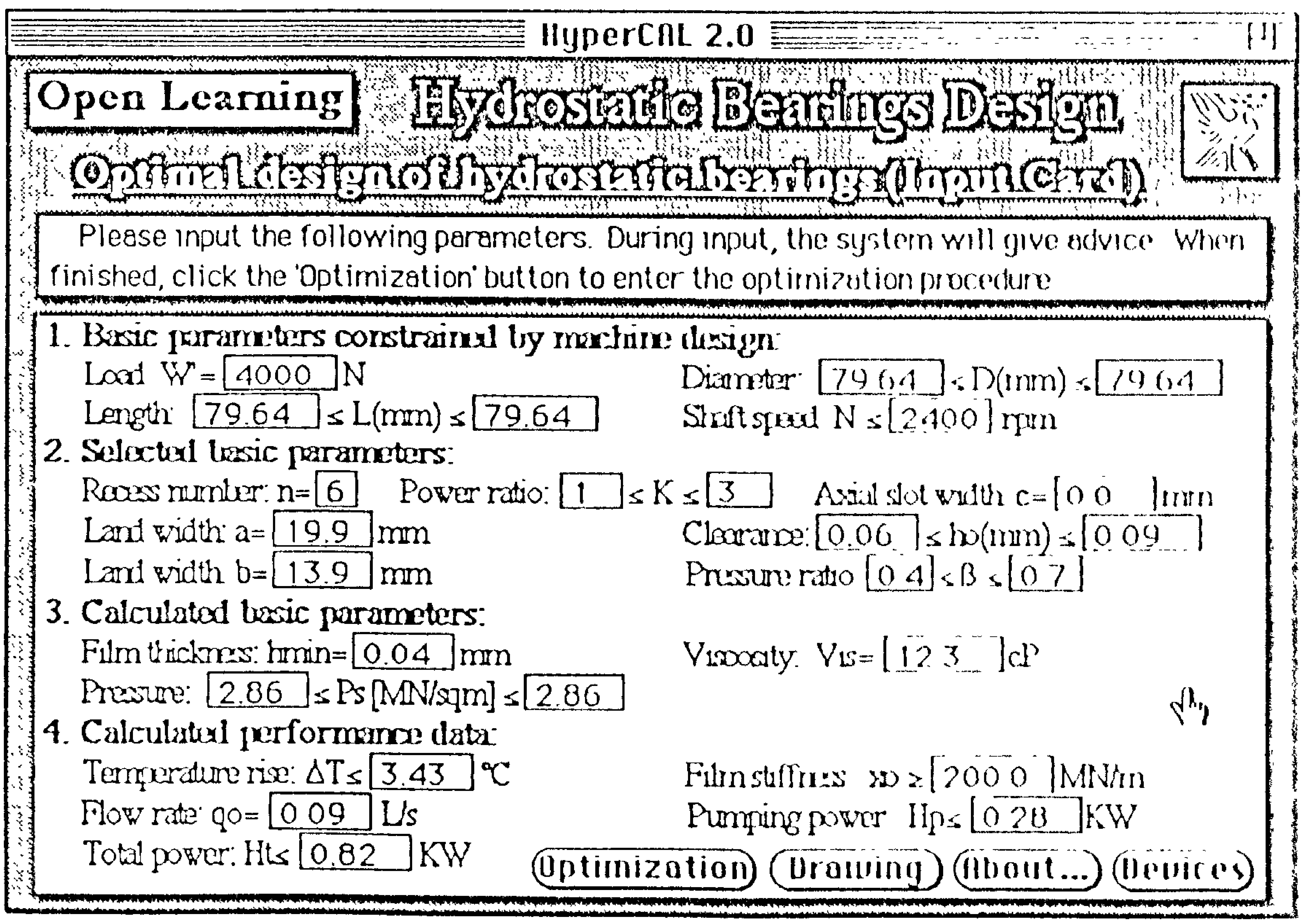
(b) A card copied from the metallurgy module



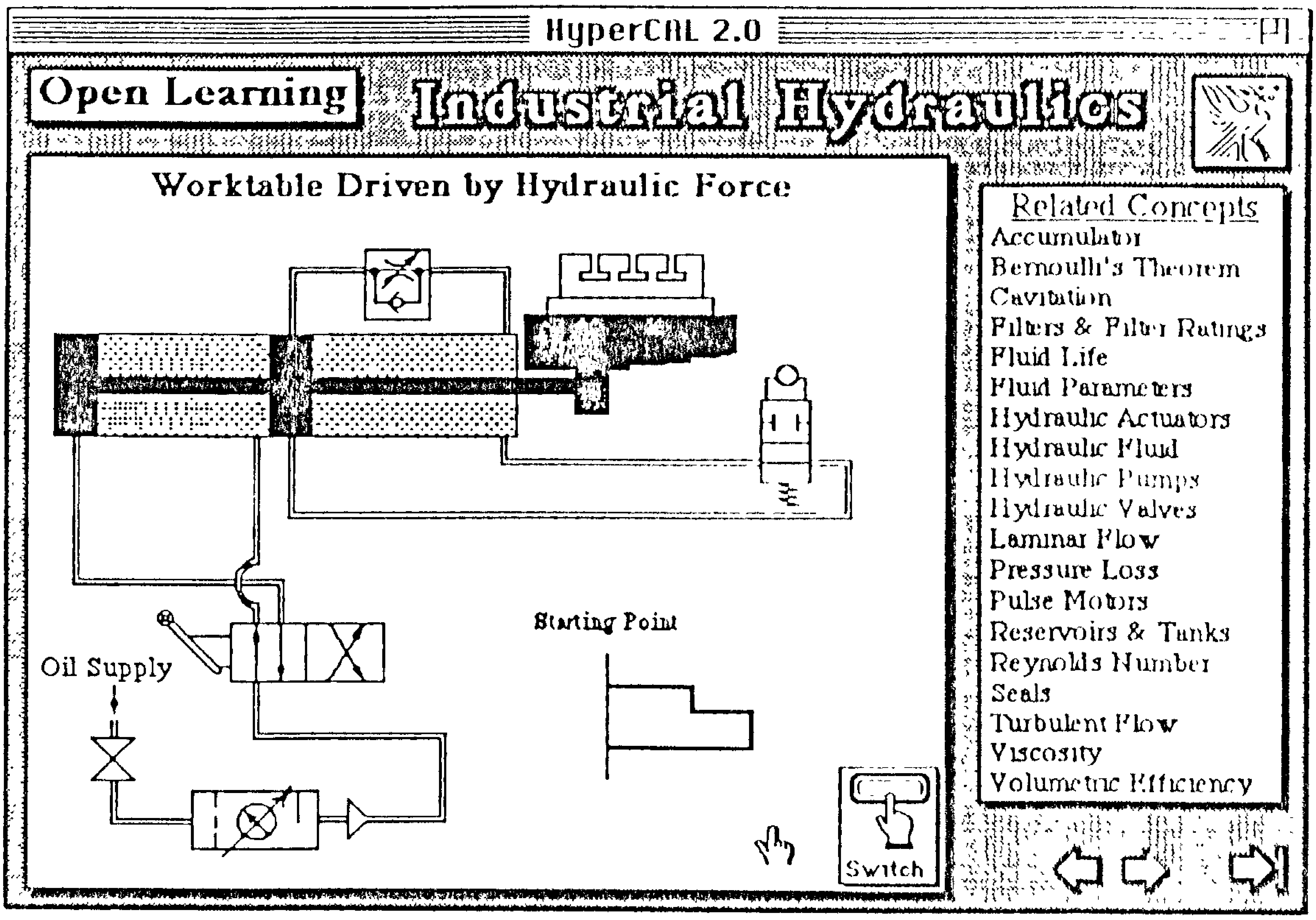
(c) A card copied from the tribology module



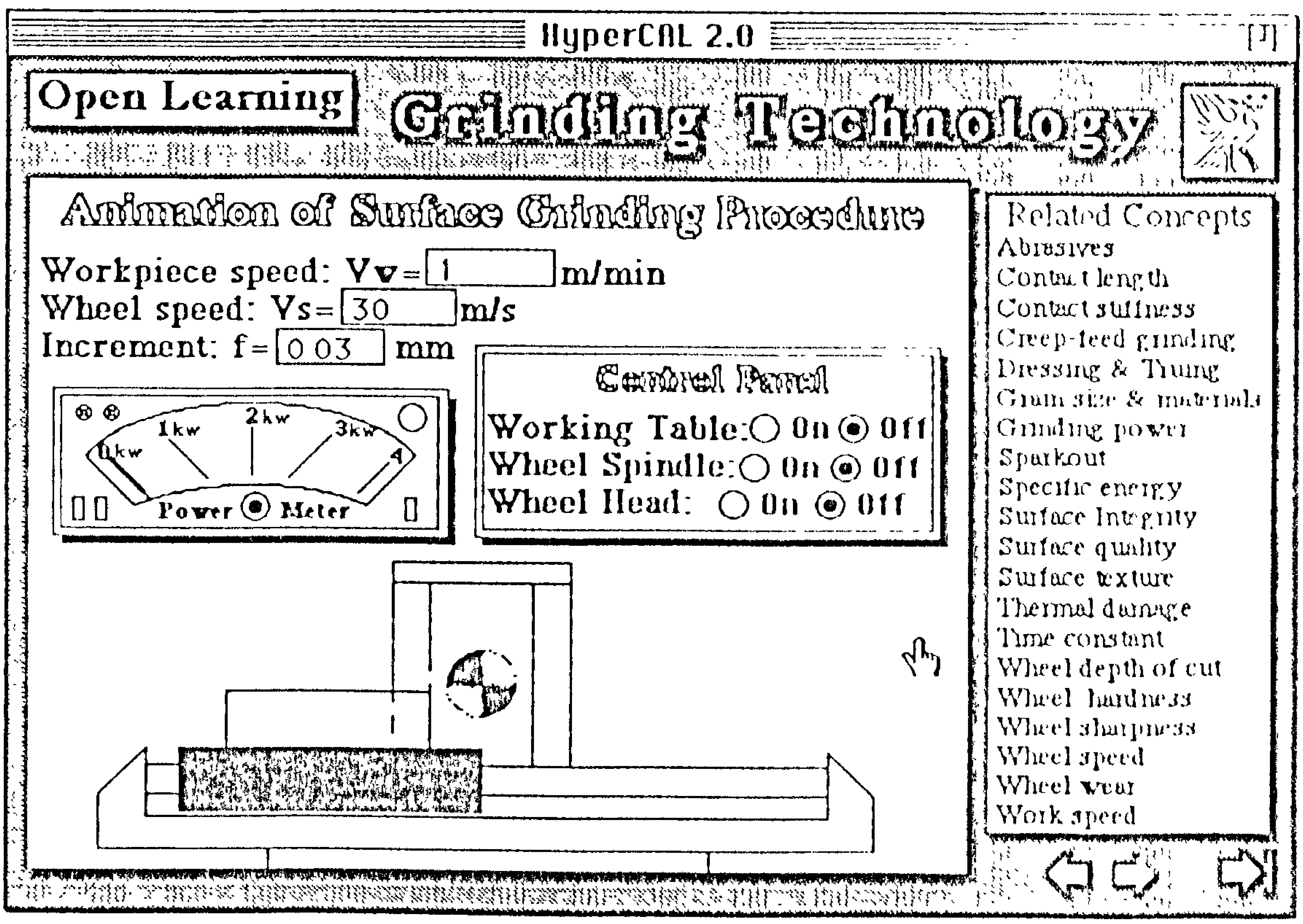
(d) A card copied from the vibration theory module



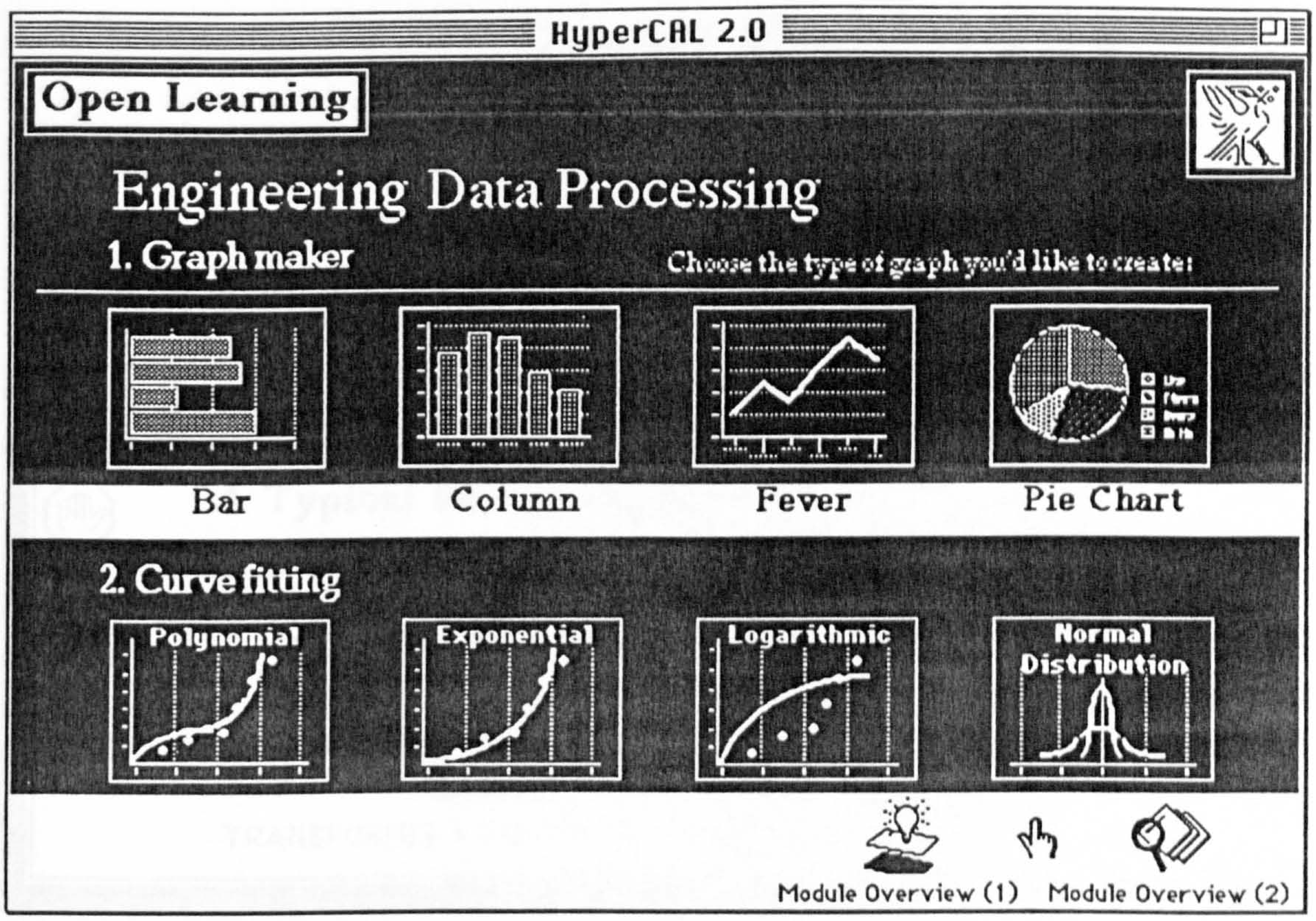
(e) A card copied from the engineering design module



(f) A card copied from the hydraulics module



(g) A card copied from the machine tools and manufacturing module



(h) A card copied from the data processing module

Figure 10.6 Exemplar cards copied from the subject modules

10.4 Practice of learning with HyperCAL

It is intended that learning should take place by interaction with subject modules within the system. The following discusses examples of the interaction of a learner with the control engineering module and with the machine tool & manufacturing module of the HyperCAL system. The examples are concerned with learning through animation/ simulation based interaction.

(1) Example 1

The control engineering module includes an example of animated simulation for power supply circuits as shown in Figure 10.7. The knowledge exists in the form of text, graphics, animation and animated simulation. To make the demonstration more attractive to a learner, the function buttons and animation/simulation within the part are accompanied by sound and music. The learner can learn the concepts by reading the

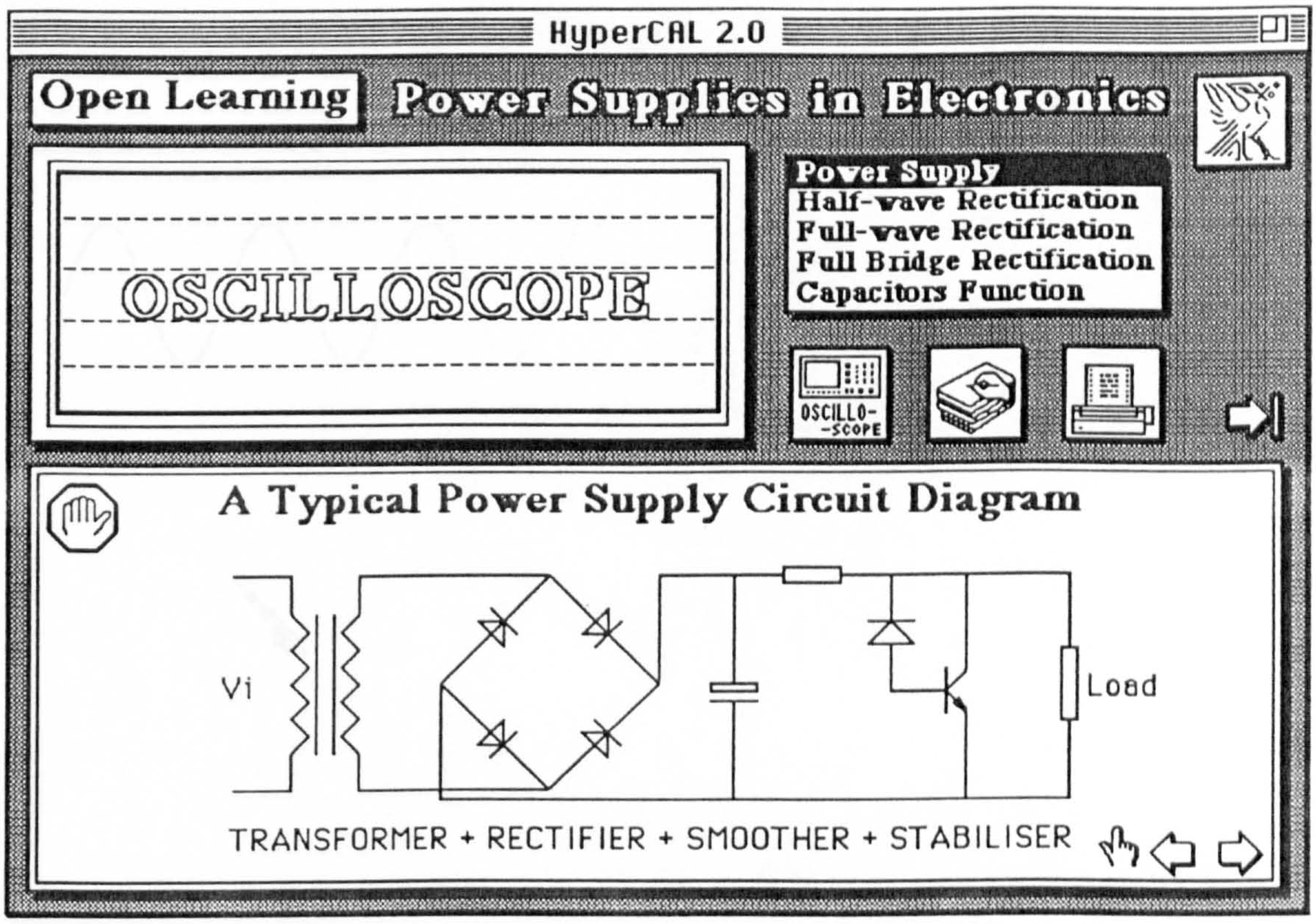
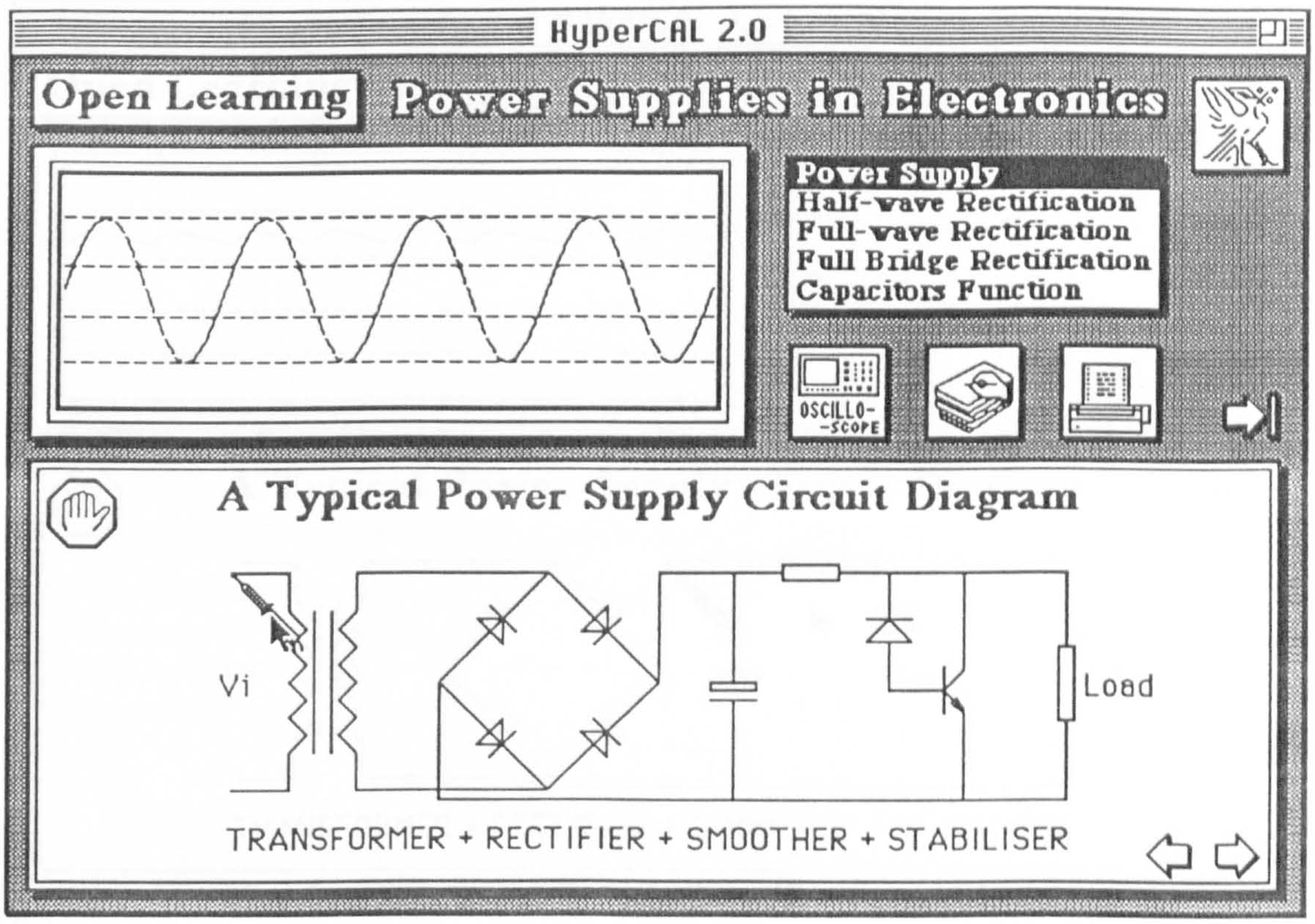
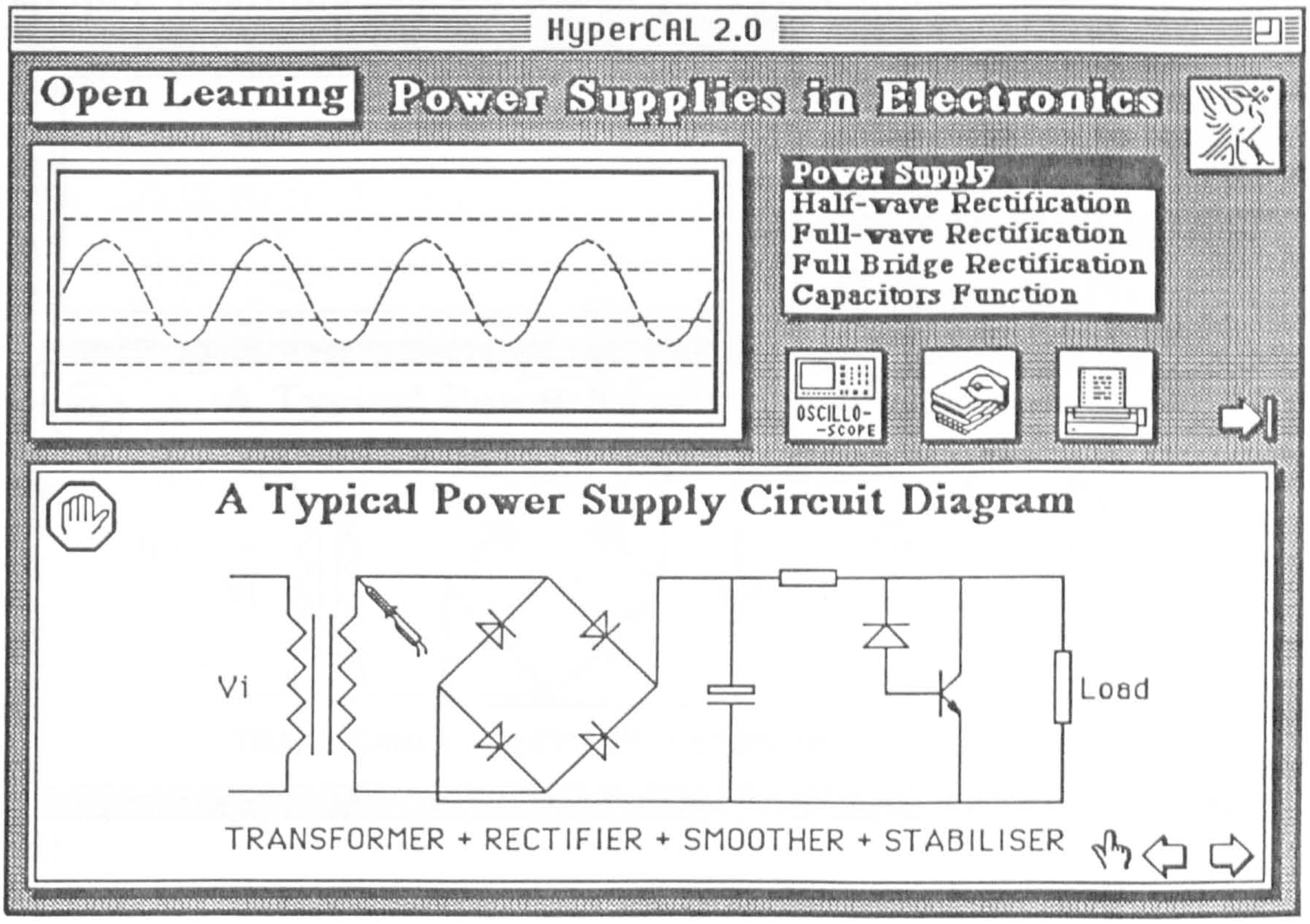


Figure 10.7 A part of control engineering module

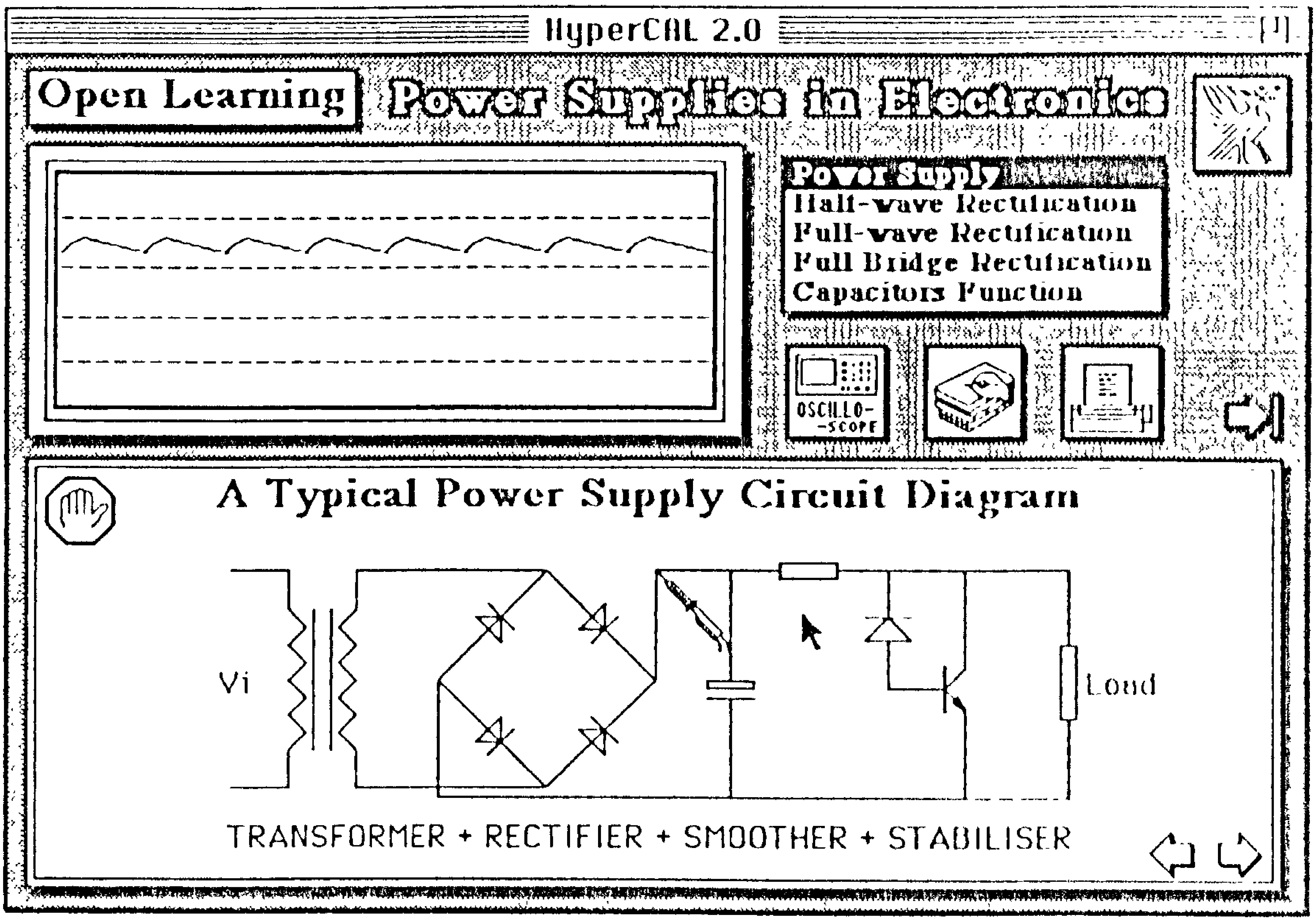
text and circuit diagrams, and get a better understanding of objective knowledge by 'playing' animation or animated simulation. For example, a learner can select the title 'Power Supply' and get the system to display the text description about a typical power supply circuit and its circuit diagram. Then, the learner can click the 'Oscilloscope' button to turn on an oscilloscope. The learner can place an oscilloscope probe on any node on the circuit diagram and observe the voltage waveform at each node. Typical positions of the probe and the corresponding waveforms at each position are animated in Figure 10.8. The figure also demonstrates a typical learning procedure of a learner 'playing' with the simulation model. Through the interaction, a learner can intuitively understand how ac voltage can be transformed to dc voltage on a power supply circuit. Clearly, the animation and animated simulation, combining experimental learning with tutorial, can assist a learner to get a better understanding of the objective knowledge. More importantly, the learner accesses and achieves the knowledge by 'playing' with the module animation or simulation. 'Playing' is a natural way of acquiring knowledge.


HyperCAL 2.0
Open Learning
Power Supplies in Electronics
Power Supply
Half-wave Rectification
Full-wave Rectification
Full Bridge Rectification
Capacitors Function
OSCILLO-SCOPE
A Typical Power Supply Circuit Diagram
Vi
Load
TRANSFORMER + RECTIFIER + SMOOTHER + STABILISER

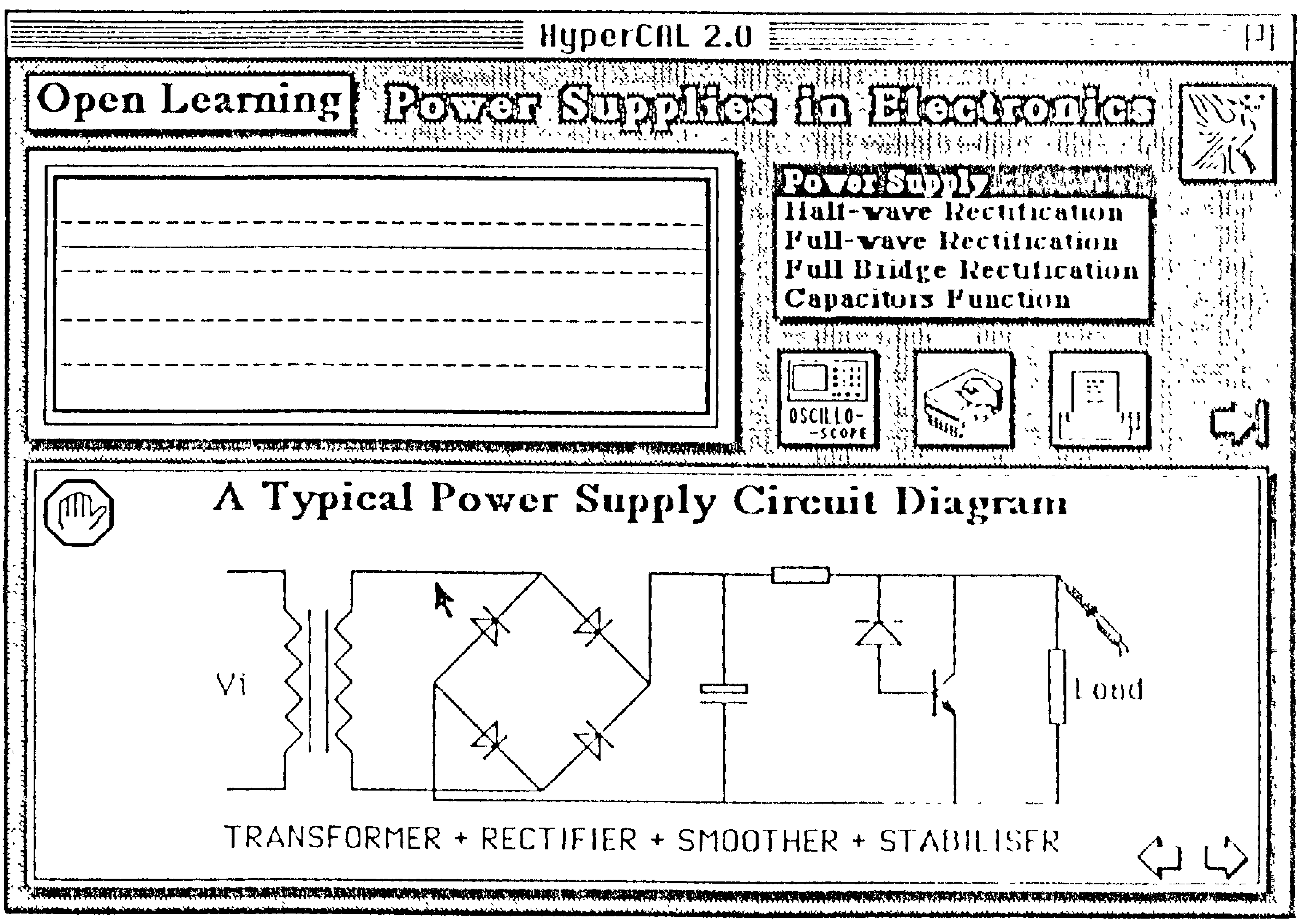
(a)


HyperCAL 2.0
Open Learning
Power Supplies in Electronics
Power Supply
Half-wave Rectification
Full-wave Rectification
Full Bridge Rectification
Capacitors Function
OSCILLO-SCOPE
A Typical Power Supply Circuit Diagram
Vi
Load
TRANSFORMER + RECTIFIER + SMOOTHER + STABILISER

(b)



(c)



(d)

Figure 10.8 A partial learning procedure by using the control engineering module

(2) Example 2

Figure 10.9 shows a grinding technology card from the machine tools and manufacturing module. The card demonstrates the animation of the surface grinding process. The inputs of the grinding process parameters such as workpiece speed V_w,

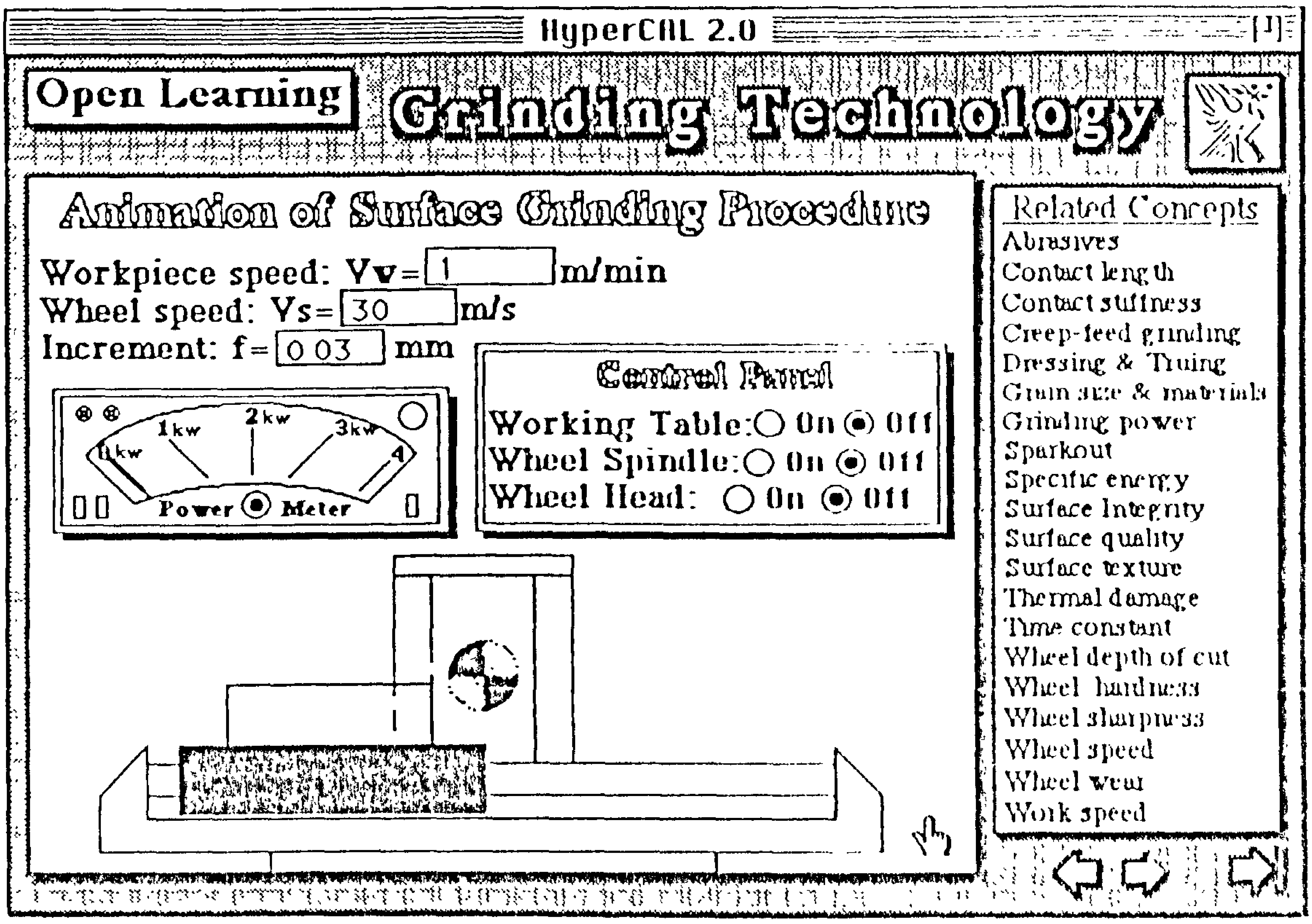


Figure 10.9 A grinding technology card of machine tools & manufacturing module

wheel speed V_s, or feed increment f can be varied. A learner can then turn on the surface grinding animation and observe how the removal rate and grinding power change during the process. Grinding power is one of the most important parameter determining workpiece surface integrity. Figure 10.10 illustrates a snapshot of the animation procedure. The interaction manipulated by a learner allows the learner to intuitively observe the grinding process and undertake interactive learning in a safe environment. The interaction incorporated with a tutorial sequence will allow a learner to achieve a better understanding of the working principles.

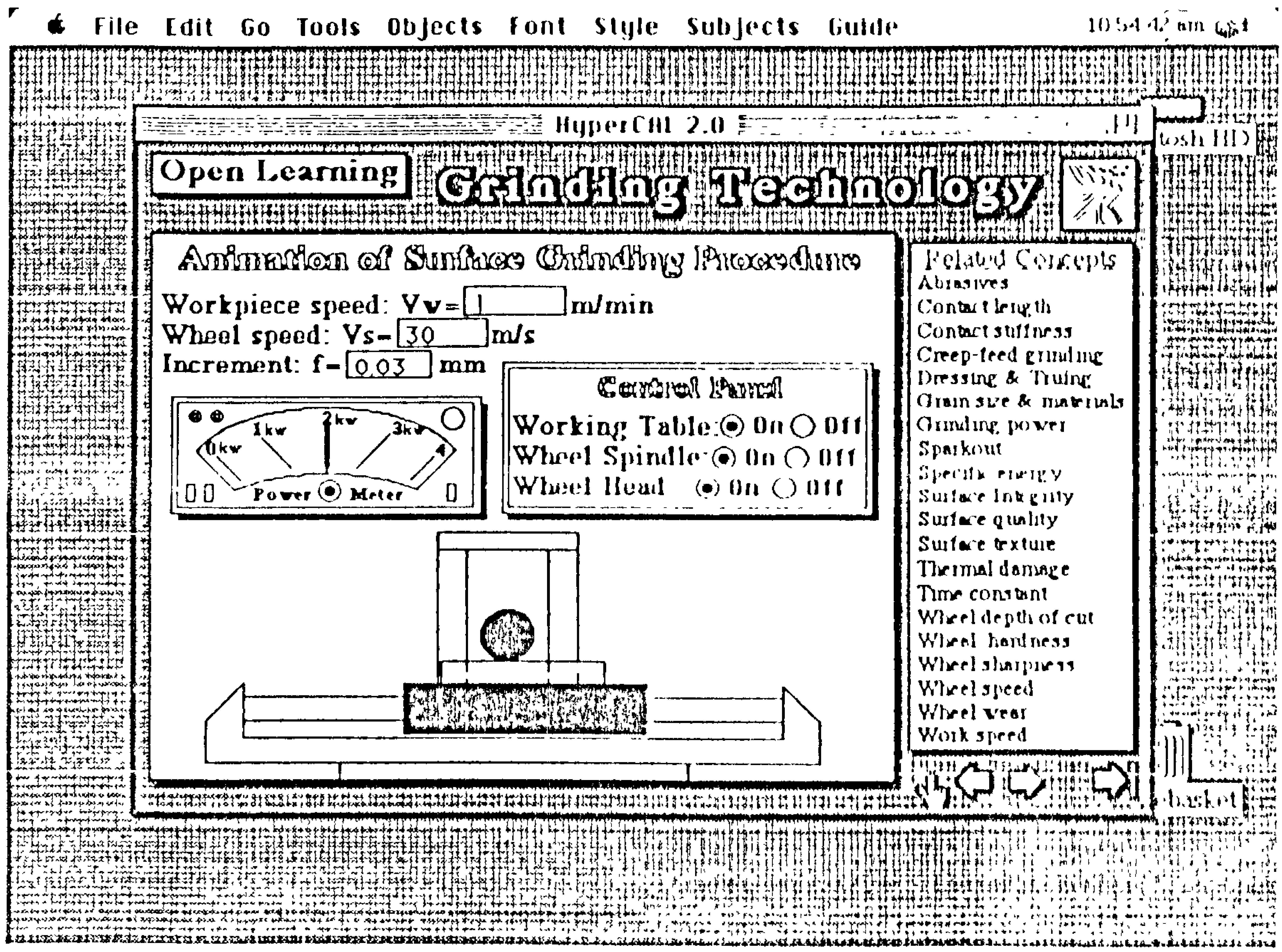


Figure 10.10 A snapshot of the grinding animation procedure

10.5 Conclusions

An illustrative hypermedia-based computer assisted learning system has been presented to demonstrate the educational potential of hypermedia technology in mechanical engineering. The system is far from fully developed as progressed so far. During the development of HyperCAL, there are many similar issues to that encountered in the development of the engineering design support systems. The issues include definition of materials, the user-interface design, human-computer interaction, cognition and the system evaluation which need to be fully addressed. More work is needed to bring the HyperCAL system to the stage where practical application in engineering education becomes feasible. The CAL techniques used for the development of computer aided design (CAD) systems need to be further investigated with particular reference to the application in the design support system. The development of a CAL system is planned for fluid film bearings design. The CAL system aims to be integrated with the design support system and will be a part of further development of the design support system

Part IV General Conclusions

Chapter 11 Conclusions and recommendations for future work

11.1 Summary of major achievements

A novel approach to developing an engineering design support system has been demonstrated based on the integration of design methodology with hypermedia and expert systems technologies. The investigation was undertaken with particular reference to the development of a design support system for externally pressurised journal bearings and a study of HCI and cognitive science issues during the development. The investigation also included the development of two hypermedia based systems, HyperCAD and HyperCAL, which is an extensive effort to explore the cognition of engineering design methodology and its computerised solutions. The major results from this research can be summarised as follows:

(1) A selection strategy has been developed for the design of externally pressurised journal bearings. The strategy is concerned with the selection of bearing type and configuration, the fluid feeding device and the bearing material. A selection model is proposed, which can be applied to the selection of the bearing type, configuration and fluid feeding device. Selection criteria are formulated for the choice of the bearing material. A number of issues are presented related to the manufacture of the bearing.

(2) A design procedure has been formulated for both hydrostatic and aerostatic journal bearings. A general design approach has been developed for externally pressurised journal bearings. The approach forms the basis for a computerised bearing design procedure.

(3) A design support system has been developed for externally pressurised journal bearings. The system is a new approach to the design of externally pressurised journal bearings through integration of expertise, optimisation techniques and

hypermedia. A novel approach to bearing selection was developed using the weighted production rules technique. The system was implemented on HyperCard on a Macintosh computer.

(4) Human-computer interaction issues within the system development were investigated. The design principles of the system user interface have been presented and development of system-designer interaction aids discussed. A method is proposed for system evaluation. The research results are of significance for the development of other engineering software systems.

(5) A hypermedia-based engineering design environment has been prototyped. The environment is coined 'HyperCAD' which is a new concept for a configurable design environment. HyperCAD allows commercially available packages to be dynamically linked through hypermedia. An engineering design process model is proposed, and is the basis of the HyperCAD development. The model is three dimensional and concerned with the design anatomy, design morphology and design objectives.

(6) A prototype hypermedia-based CAL system 'HyperCAL' has been developed for education in mechanical engineering. A 'spine' style structure is proposed for the development of courseware modules in HyperCAL. The development issues are presented with particular reference to the animation and simulation techniques. The relationship between hypermedia and learning is explored and further clarified.

11.2 Conclusions

Some conclusions with regard to the investigation hypothesis can be summarised as follows:

(1) It has been shown the integration of design expertise, AI techniques and hypertext offers significant advantages in the areas of bearing selection, bearing optimisation, dynamic linking of design activities, and computer assisted learning.

(2) The main advantages compared to conventional design software are:

- Explanatory features available on demand.
- Integration of graphical, textual and computational features.
- An intuitive HCI.
- The power of AI techniques to achieve flexible solutions.

(3) The main disadvantages of the new approach are:

- The expertise required to integrate specialist problems with AI techniques and hypermedia.
- The inflexibility of the system when modifications are required. For example, it is too much work to alter the selection dialogue/output cards.
- The difficulty of obtaining informed user viewpoints on the developed system.

11.3 Recommendations for future work

As regards future work on the research, the following is suggested:

(1) A systematic evaluation of the design support system. The evaluation should be concerned with all aspects of the system based on the evaluation criteria established and the extended checklists of criteria.

(2) The validation and modification of the design support system.

(3) The further development of HyperCAD. The development should tackle the problems of data communication between different facilities, simultaneously sharing data, downstream flow of design idea and concepts, and the integration of AI with hypermedia. Completely solving these problems is essential to bring HyperCAD to a practical application stage. Using HyperCAD in fluid film bearings design is a preferred area of application.

(4) Further investigation of the cognition issues within a computer based engineering design process. The principles of design knowledge transfer, through a computer based system and its interaction with a designer, should be clarified.

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Appendices

Appendix I A XCMD Pascal program for adding a menu to a HyperCard menu bar

```
UNIT DummyUnit;

INTERFACE

USES MemTypes, QuickDraw, OSIntf, ToolIntf, PasLibIntf, HyperXCmd;

PROCEDURE ENTRYPOINT(paramPtr: XCmdPtr);

IMPLEMENTATION

TYPE Str31 = String[31];

PROCEDURE AddMenu(paramPtr: XCmdPtr);          FORWARD;

    PROCEDURE ENTRYPOINT(paramPtr: XCmdPtr);

        BEGIN
            AddMenu(paramPtr);
        END;

    PROCEDURE AddMenu(paramPtr: XCmdPtr);

        CONST       minParamCount = 3;

        VAR                 menuList:               Str255;
                            menuName:               Str255;
                            tempStr:                Str255;
                            menuID:                 LongInt;
                            myMenuList:             Handle;
                            myMenuHandle:           MenuHandle;

{$I XCmdGlue.inc } {Includes the glue routines}

    PROCEDURE Fail(errStr:  Str255); {Exit returning an error message}

        BEGIN
            paramPtr^.returnValue := PasToZero(errStr); {load the result}
```

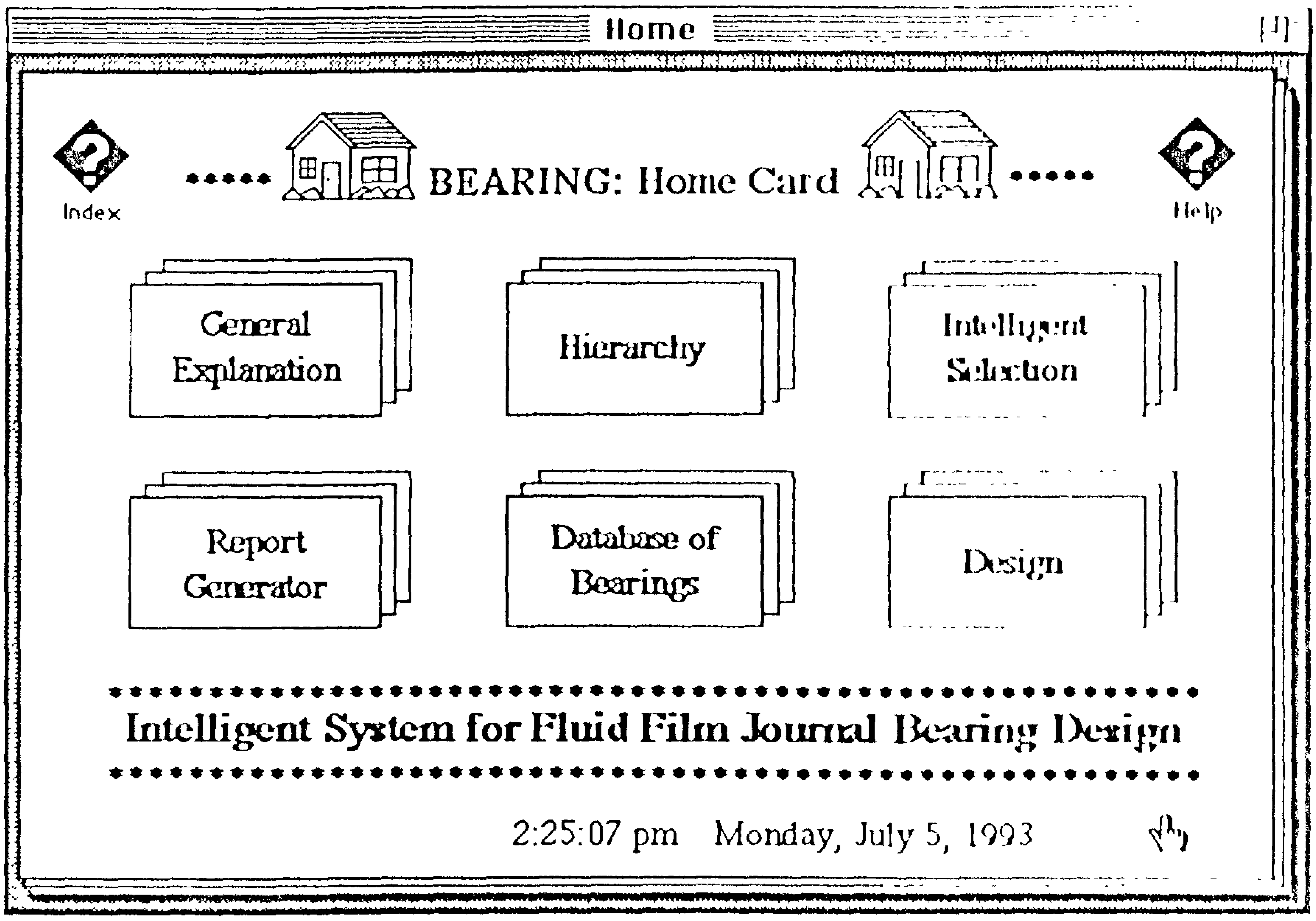
```
            EXIT(AddMenu); {Leave the XCMD}
        END; {Fail}

    PROCEDURE CheckParamCount; {checks for the correct parameter count}

        VAR      numParams:      Integer;

        BEGIN
            numParams := paramPtr^.paramCount; {store the number of parameters passed}
            IF (numParams <> minParamCount)
            THEN Fail('Form: AddMenu "MenuName",
                        MenuNumber,MenuList');
        END; {CheckParamCount}

    BEGIN {main}
        CheckParamCount; {make sure there's enough parameters}
        ZeroToPas(paramPtr^.params[1]^,menuName); {convert the menu name}
        ZeroToPas(paramPtr^.params[2]^,tempStr);
        menuID := StrToLong(tempStr); {convert the menu number}
        IF menuID <= 0 THEN Fail('Zero and negative numbers not allowed');
        ZeroToPas(paramPtr^.params[3]^,menuList); {convert the menu list}
        IF menuList = '' THEN menuList := ' '; {make a null list work correctly}
        myMenuHandle := NewMenu(MenuID,menuName); {create a new menu item}
        IF myMenuHandle = NIL THEN Fail('Unable to get menu handle');
        AppendMenu(myMenuHandle,menuList); {adds menuList to end of menu}
        InsertMenu(myMenuHandle,0); {adds the menu to the end of the menu list}
        DrawMenuBar; {draw the menu bar with the new menu}
    END; {main}
END.
```

Appendix II A XCMD Pascal program for removing a menu from a HyperCard menu bar

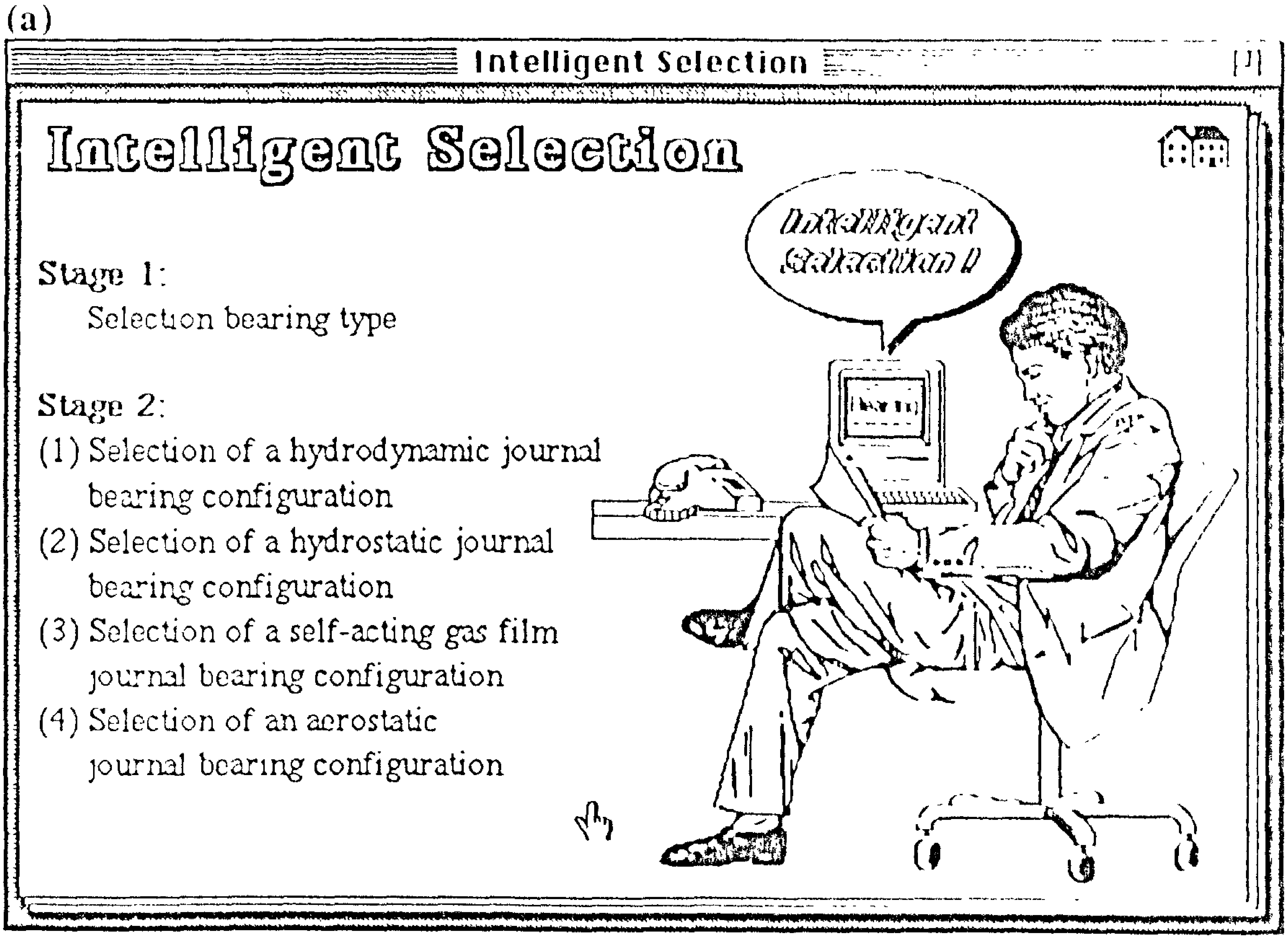
```
UNIT DummyUnit;

INTERFACE

USES MemTypes, QuickDraw, OSIntf, ToolIntf, HyperXCmd;

PROCEDURE ENTRYPOINT(paramPtr: XCmdPtr);

IMPLEMENTATION

TYPE Str31 = String[31];

PROCEDURE ClearMenu(paramPtr: XCmdPtr);        FORWARD;

 PROCEDURE ENTRYPOINT(paramPtr: XCmdPtr);

BEGIN
  ClearMenu(paramPtr);
END;

PROCEDURE ClearMenu(paramPtr: XCmdPtr);

      CONST        minParamCount = 1;

      VAR          tempStr:                        Str255;
                   menuID:                         LongInt;
                   myMenuHandle:                   MenuHandle;

{$I XCmdGlue.inc } {Includes the glue routines}

      PROCEDURE Fail(errStr:       Str255); {Exit returning an error message}

            BEGIN
                   paramPtr^.returnValue := PasToZero(errStr); {load the result}
                   EXIT(ClearMenu); {Leave the XCMD}
            END; {Fail}
```

```
PROCEDURE CheckParamCount; {checks for the correct parameter count}

        VAR             numParams:              Integer;

        BEGIN
                numParams := paramPtr^.paramCount; {store the number of
parameters passed}
                IF (numParams <> minParamCount)
                THEN Fail('Form: ClearMenu MenuID');
        END; {CheckParamCount}

BEGIN {main}
        CheckParamCount; {make sure there's enough parameters}
        ZeroToPas(paramPtr^.params[1]^,tempStr);
        menuID := StrToLong(tempStr); {get and store the ID}
        IF menuID <= 0 THEN Fail('Zero and negative numbers not allowed');
        myMenuHandle := GetMHandle(MenuID); {disposeMenu needs a handle}
        IF myMenuHandle = NIL THEN Fail('Cannot find that menu item');
        deleteMenu(MenuID); {must remove it from the menu list before deleting}
        disposeMenu(myMenuHandle); {delete the menu item}
        DrawMenuBar; {draw the menu bar without the item}
END; {main}

END. {XCMD}
```

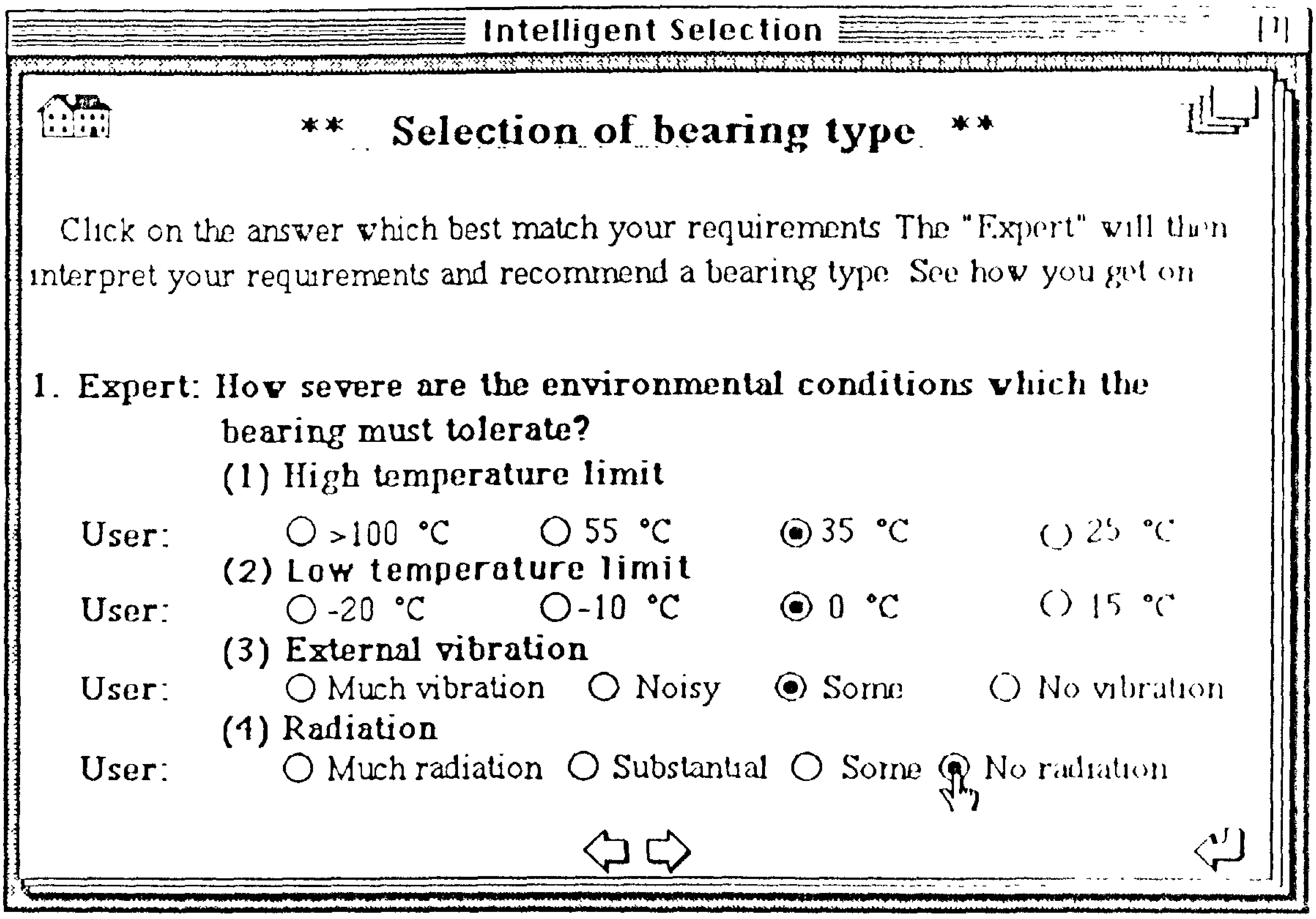
Appendix III The complete design procedure for an aerostatic journal bearing with pocketed orifice feeding type



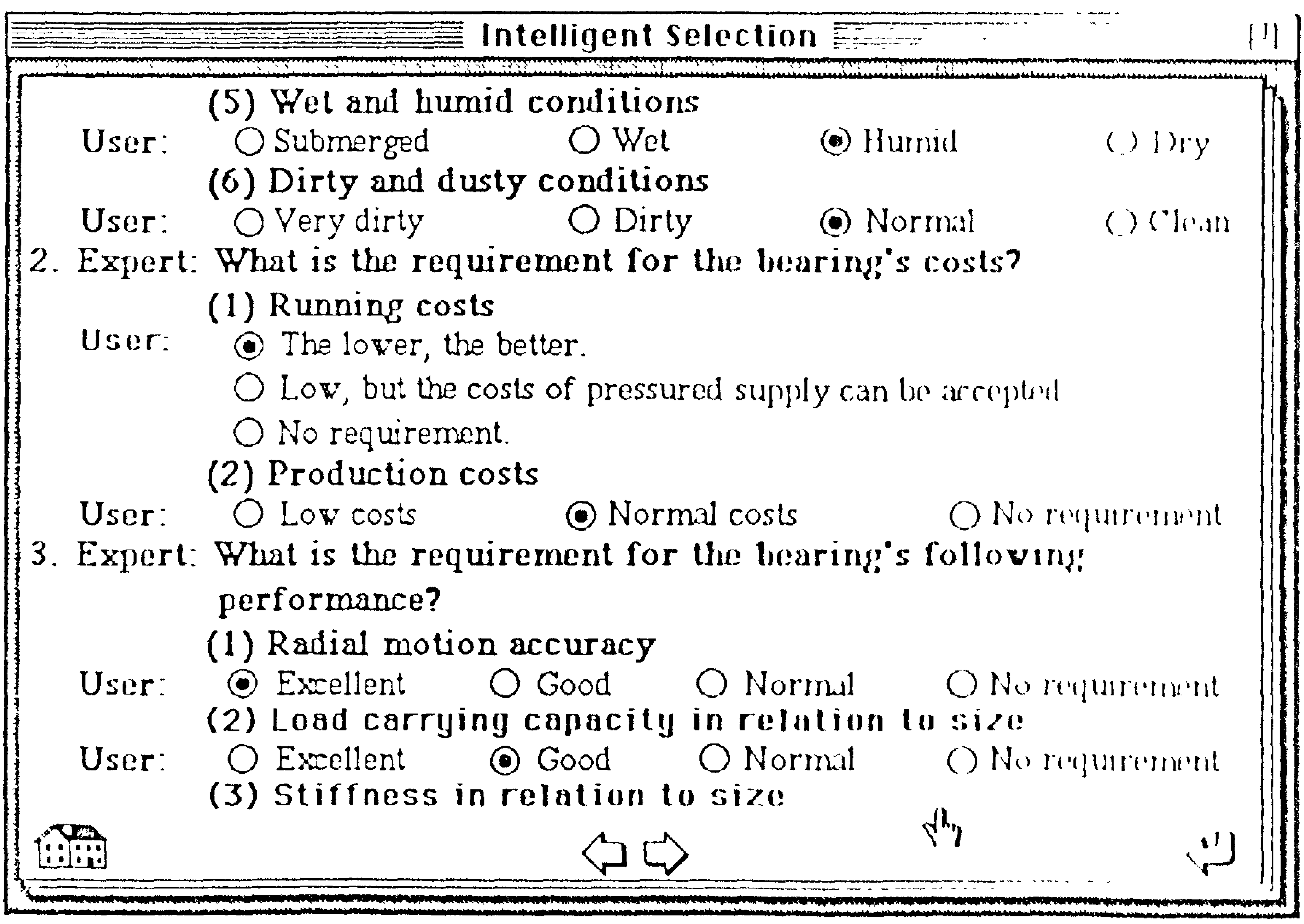
(a)



(b)


Intelligent Selection
** Selection of bearing type **
Click on the answer which best match your requirements The "Expert" will then interpret your requirements and recommend a bearing type. See how you get on
1. Expert: How severe are the environmental conditions which the bearing must tolerate?
(1) High temperature limit
User: >100 °C 55 °C 35 °C 25 °C
(2) Low temperature limit
User: -20 °C -10 °C 0 °C 15 °C
(3) External vibration
User: Much vibration Noisy Some No vibration
(4) Radiation
User: Much radiation Substantial Some No radiation

(c)


Intelligent Selection
(5) Wet and humid conditions
User: Submerged Wet Humid Dry
(6) Dirty and dusty conditions
User: Very dirty Dirty Normal Clean
2. Expert: What is the requirement for the bearing's costs?
(1) Running costs
User: The lower, the better.
Low, but the costs of pressured supply can be accepted
No requirement.
(2) Production costs
User: Low costs Normal costs No requirement
3. Expert: What is the requirement for the bearing's following performance?
(1) Radial motion accuracy
User: Excellent Good Normal No requirement
(2) Load carrying capacity in relation to size
User: Excellent Good Normal No requirement
(3) Stiffness in relation to size

(d)

Intelligent Selection

User: ○ Excellent ◉ Good ○ Normal ○ No requirement

(4) Damping

User: ○ Excellent ◉ Good ○ Normal ○ No requirement

(5) High speed

User: ◉ Excellent ○ Good ○ Normal ○ No requirement

(6) Temperature rise due to the bearing operation

User: ◉ Lower ○ Low ○ Normal ○ No requirement

(7) Central control

User: ◉ Excellent ○ Good ○ Normal ○ No requirement

(8) Durability

User: ○ Excellent ◉ Good ○ Normal ○ No requirement

(9) Maintenance

User: ○ Excellent ◉ Good ○ Normal ○ No requirement

4. Expert: What is the requirement for the bearing in operation?

(1) Starting torque

User: ○ Very low ◉ Low ○ Normal ○ No requirement

(2) Running torque

User: ○ Very low ◉ Low ○ Normal ○ No requirement

(e)

Intelligent Selection

5. Expert: What is the requirement for the bearing's following performance?

(1) Running noise

User: ◉ Little noise ○ Normal ○ No requirement

(2) Frequent stop-starts

User: ◉ Very frequent ○ Frequent ○ Normal ○ No requirement

(3) Prevention of contamination of surroundings and products

User: ○ No contamination ◉ Normal need ○ No requirement

(4) Availability of standard parts

User: ○ Necessary ◉ No requirement

(5) External dimension

User: ○ The smaller, the better ◉ Normal ○ No requirement

6. Expert: What is the requirement for the bearing to be easily designed and manufactured?

(1) Easy of design

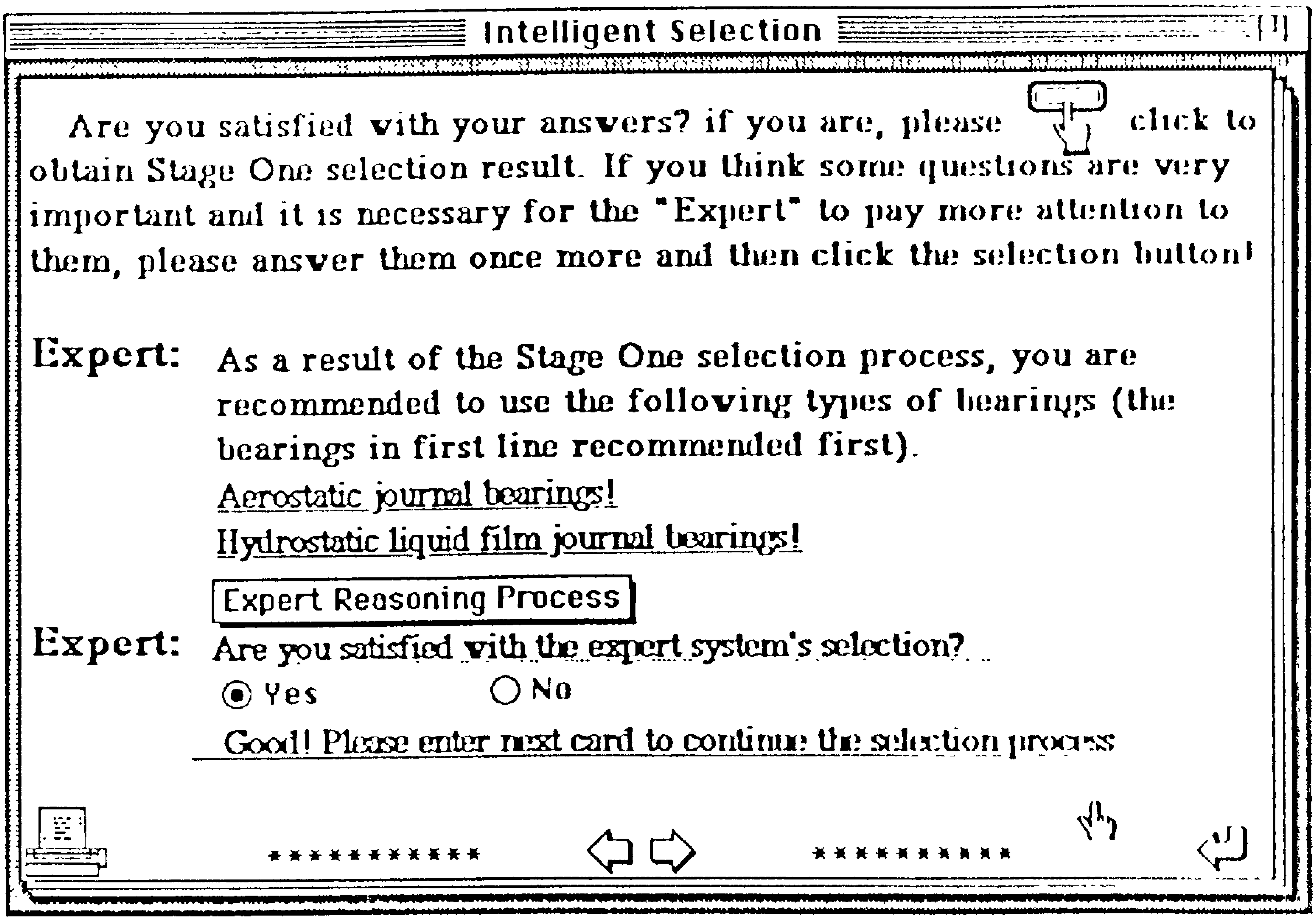
User: ○ Excellent ◉ Good ○ Normal ○ No requirement

(2) Easy of manufacture

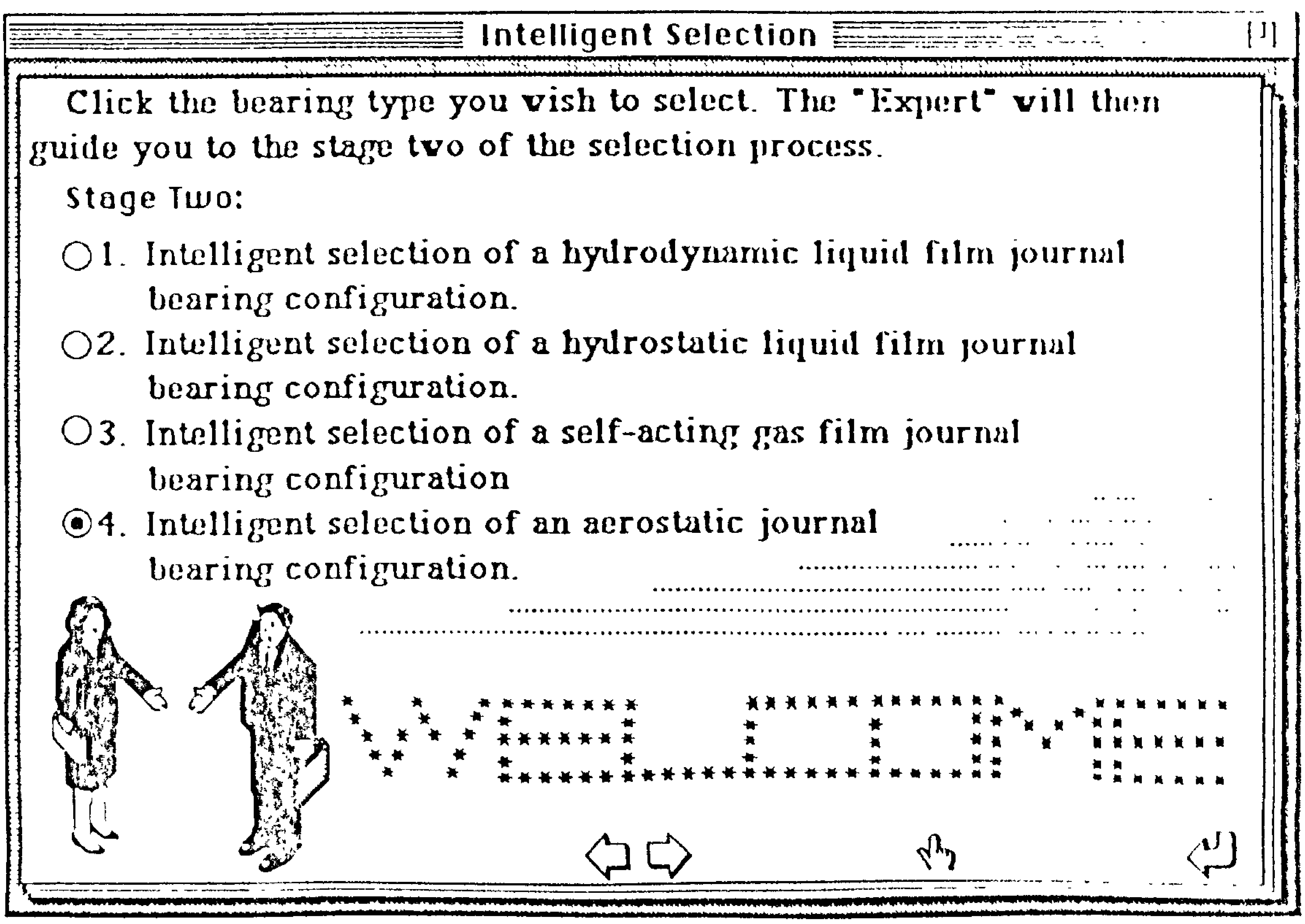
User: ○ Excellent ◉ Good ○ Normal ○ No requirement

***** *****

(f)


Intelligent Selection
Are you satisfied vith your ansvers? if you are, please click to obtain Stage One selection result. If you think some questions are very important and it is necessary for the "Expert" to pay more attention to them, please ansver them once more and then click the selection button!
Expert: As a result of the Stage One selection process, you are recommended to use the following types of bearings (the bearings in first line recommended first).
Aerostatic journal bearings!
Hydrostatic liquid film journal bearings!
Expert Reasoning Process
Expert: Are you satisfied vith the expert system's selection?
Yes
No
Good! Please enter next card to continue the selection process

(g)


Intelligent Selection
Click the bearing type you vish to select. The "Expert" vill then guide you to the stage tvo of the selection process.
Stage Two:
1. Intelligent selection of a hydrodynamic liquid film journal bearing configuration.
2. Intelligent selection of a hydrostatic liquid film journal bearing configuration.
3. Intelligent selection of a self-acting gas film journal bearing configuration
4. Intelligent selection of an aerostatic journal bearing configuration.
WELCOME

(h)

Intelligent Selection

Selection of an aerostatic journal bearing configuration

Continue specifying the bearing requirements. The "Expert" will then interpret your requirements and a bearing configuration will be recommended.

1. Expert: What is the bearing's performance requirement?

(1) Load carrying capacity in axial direction
User: ( ) Excellent (•) Good ( ) Normal ( ) No requirement

(2) Load carrying capacity in radial direction
User: (•) Excellent ( ) Good ( ) Normal ( ) No requirement

(3) Positioning accuracy in axial direction
User: ( ) Excellent (•) Good ( ) Normal ( ) No requirement

(4) Positioning accuracy in radial direction
User: (•) Excellent ( ) Good ( ) Normal ( ) No requirement

(5) Positioning accuracy for angular alignment
User: ( ) Excellent ( ) Good (•) Normal ( ) No requirement

(6) Stiffness in radial direction
User: ( ) Excellent ( ) Good ( ) Normal ( ) No requirement

(i)

Intelligent Selection

(7) Stiffness in axial direction
User: ( ) Excellent ( ) Good (•) Normal ( ) No requirement

2. Expert: What is the requirement for the bearing's production cost, ease of design and ease of manufacture?

(1) Production cost
User: ( ) Lowest cost (•) Normal cost ( ) No requirement

(2) Ease of design
User: ( ) Excellent (•) Good ( ) Normal ( ) No requirement

(3) Ease of manufacture
User: (•) Excellent ( ) Good ( ) Normal ( ) No requirement

3. Expert: What are the bearing's performance requirements?

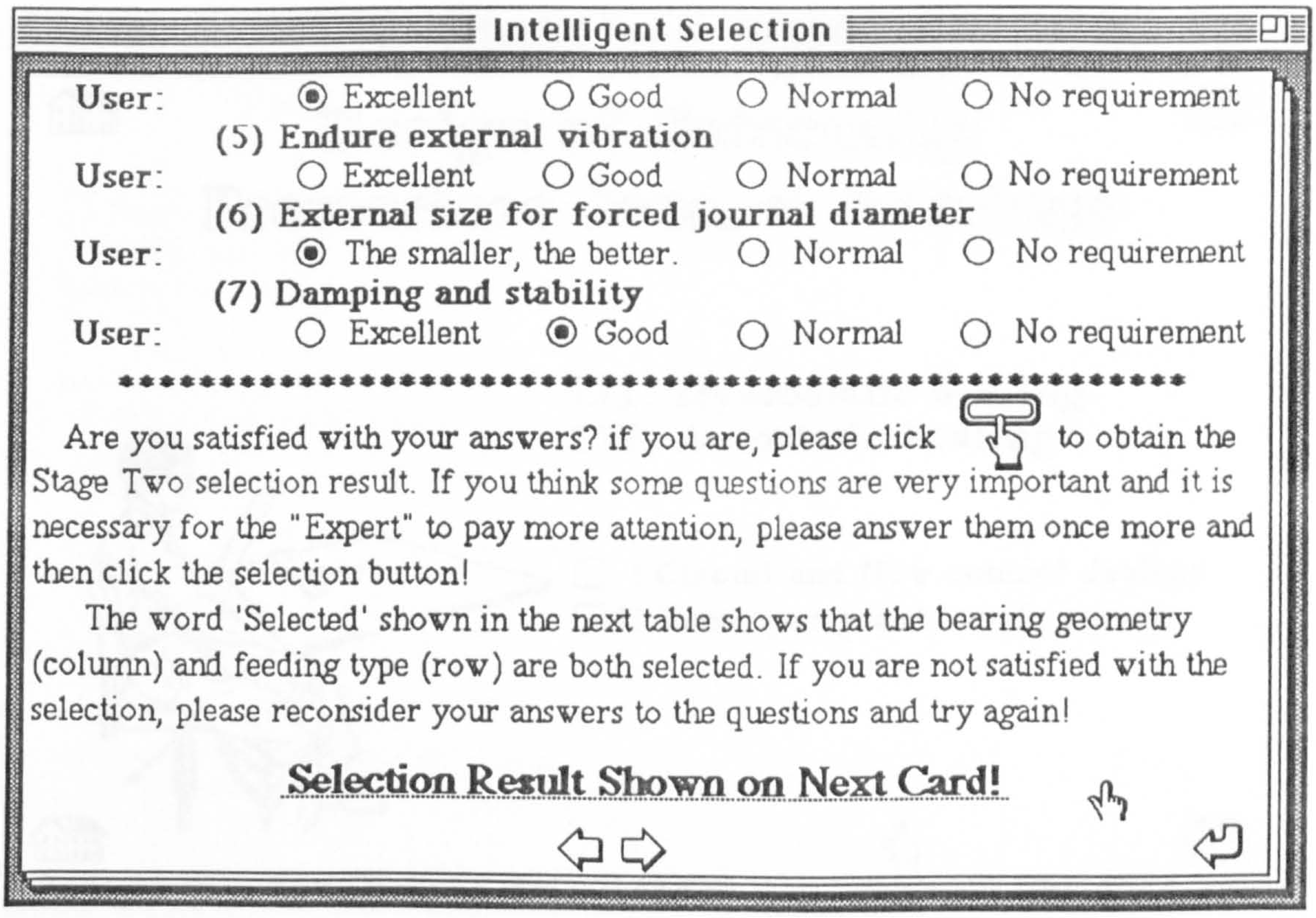
(1) Self-aligning ability
User: ( ) Excellent ( ) Good (•) Normal ( ) No requirement

(2) Combined axial and radial load carrying ability
User: ( ) Excellent (•) Good ( ) Normal ( ) No requirement

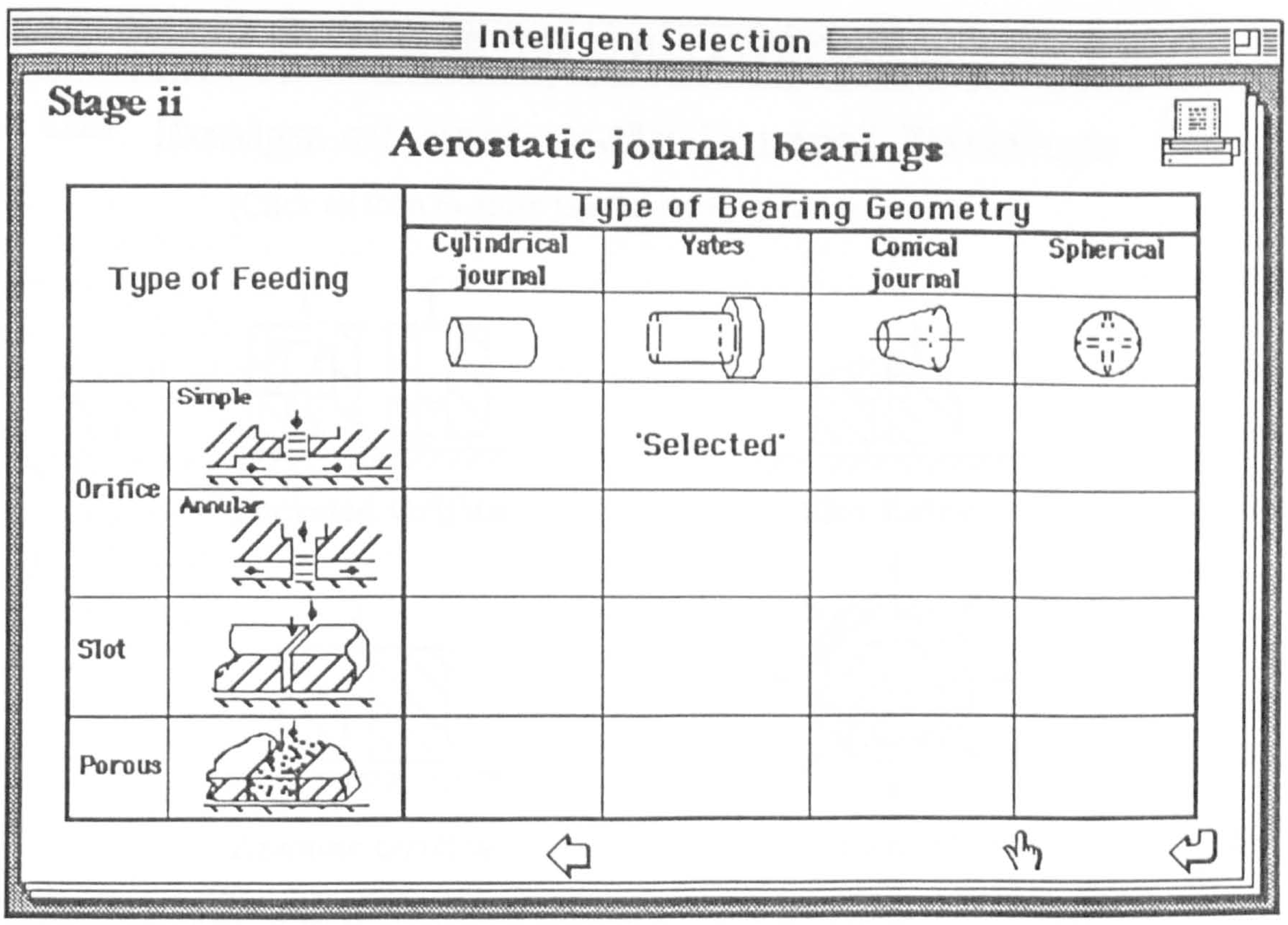
(3) Ease of maintenance
User: ( ) Excellent (•) Good ( ) Normal ( ) No requirement

(4) Economy of flow rate, power and number of parts

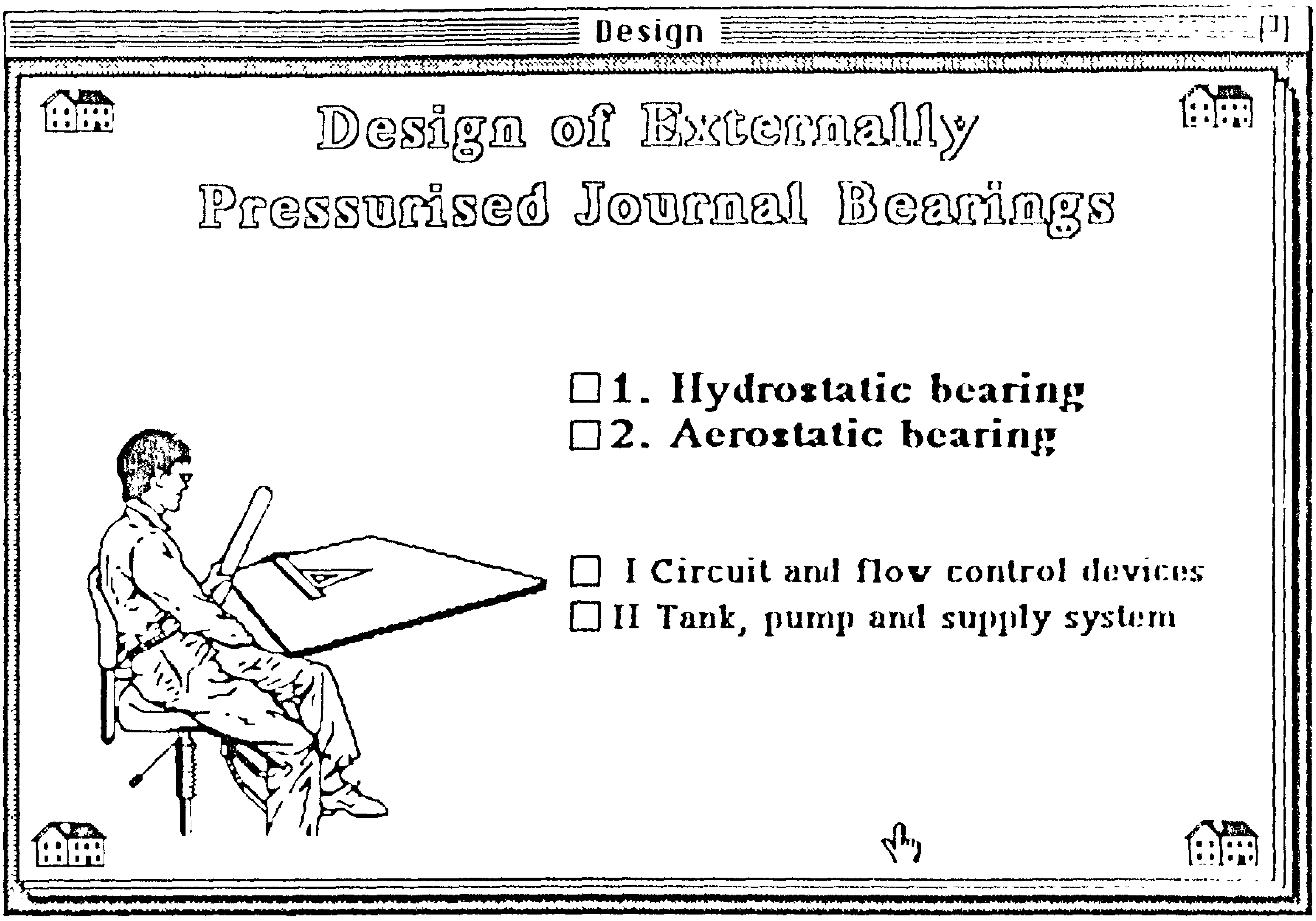
(j)


Intelligent Selection
User: Excellent Good Normal No requirement
(5) Endure external vibration
User: Excellent Good Normal No requirement
(6) External size for forced journal diameter
User: The smaller, the better. Normal No requirement
(7) Damping and stability
User: Excellent Good Normal No requirement
Are you satisfied with your answers? if you are, please click to obtain the Stage Two selection result. If you think some questions are very important and it is necessary for the "Expert" to pay more attention, please answer them once more and then click the selection button!
The word 'Selected' shown in the next table shows that the bearing geometry (column) and feeding type (row) are both selected. If you are not satisfied with the selection, please reconsider your answers to the questions and try again!
Selection Result Shown on Next Card!

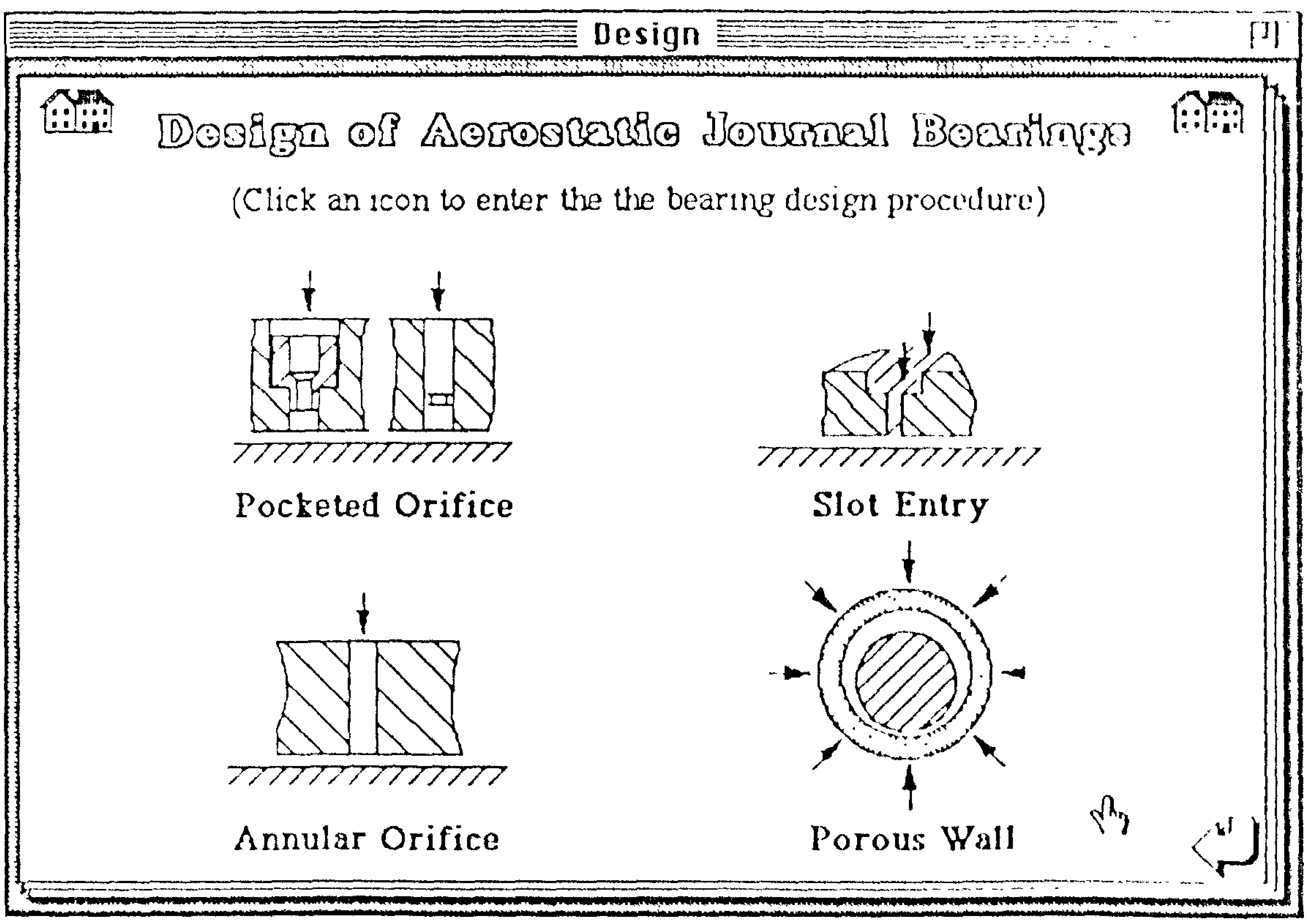
(k)


Intelligent Selection
Stage ii
Aerostatic journal bearings
Type of Feeding
Type of Bearing Geometry
Cylindrical journal
Yates
Conical journal
Spherical
Orifice
Simple
Annular
'Selected'
Slot
Porous

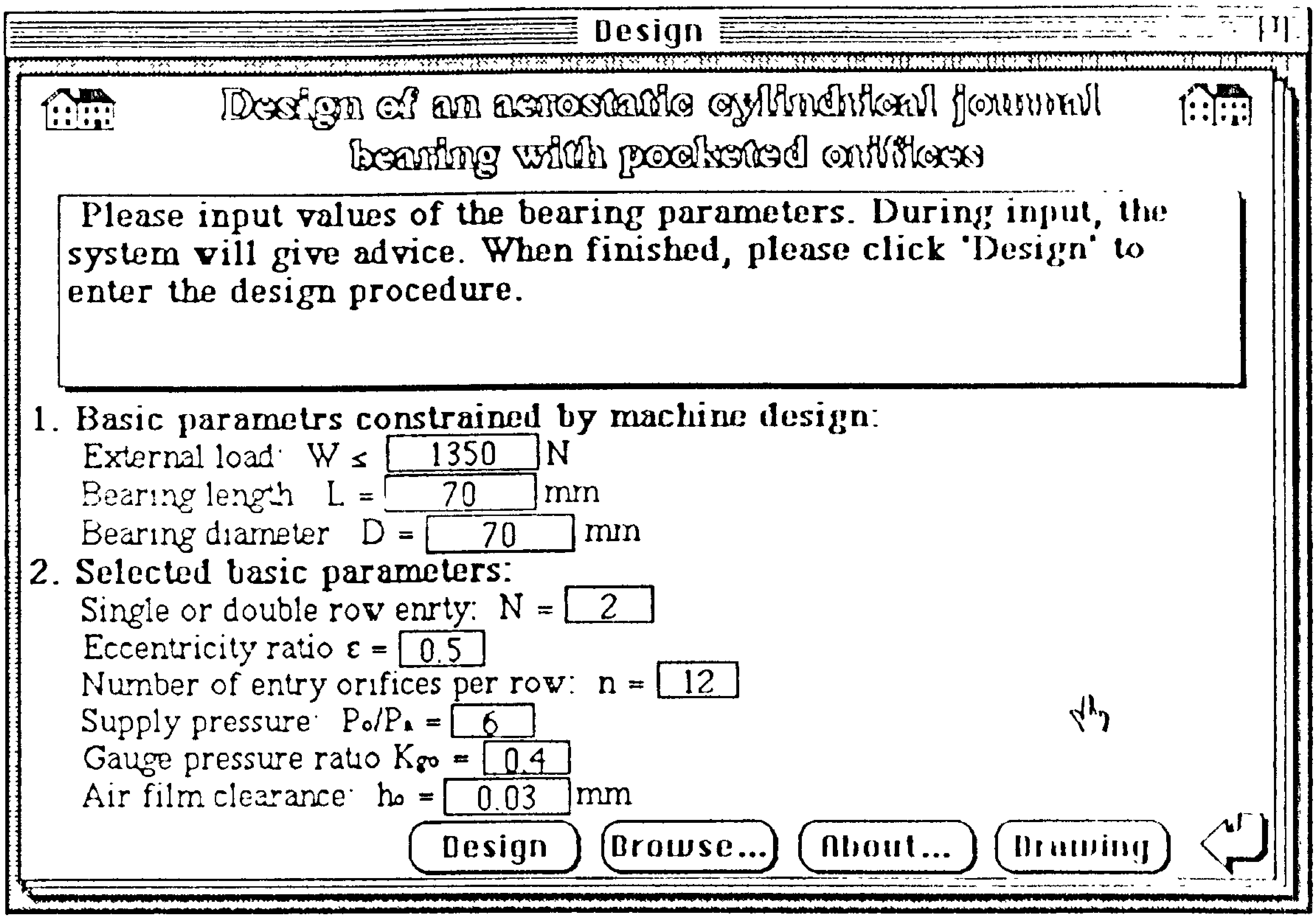
(l)


Design
Design of Externally
Pressurised Journal Bearings
1. Hydrostatic bearing
2. Aerostatic bearing
I Circuit and flow control devices
II Tank, pump and supply system

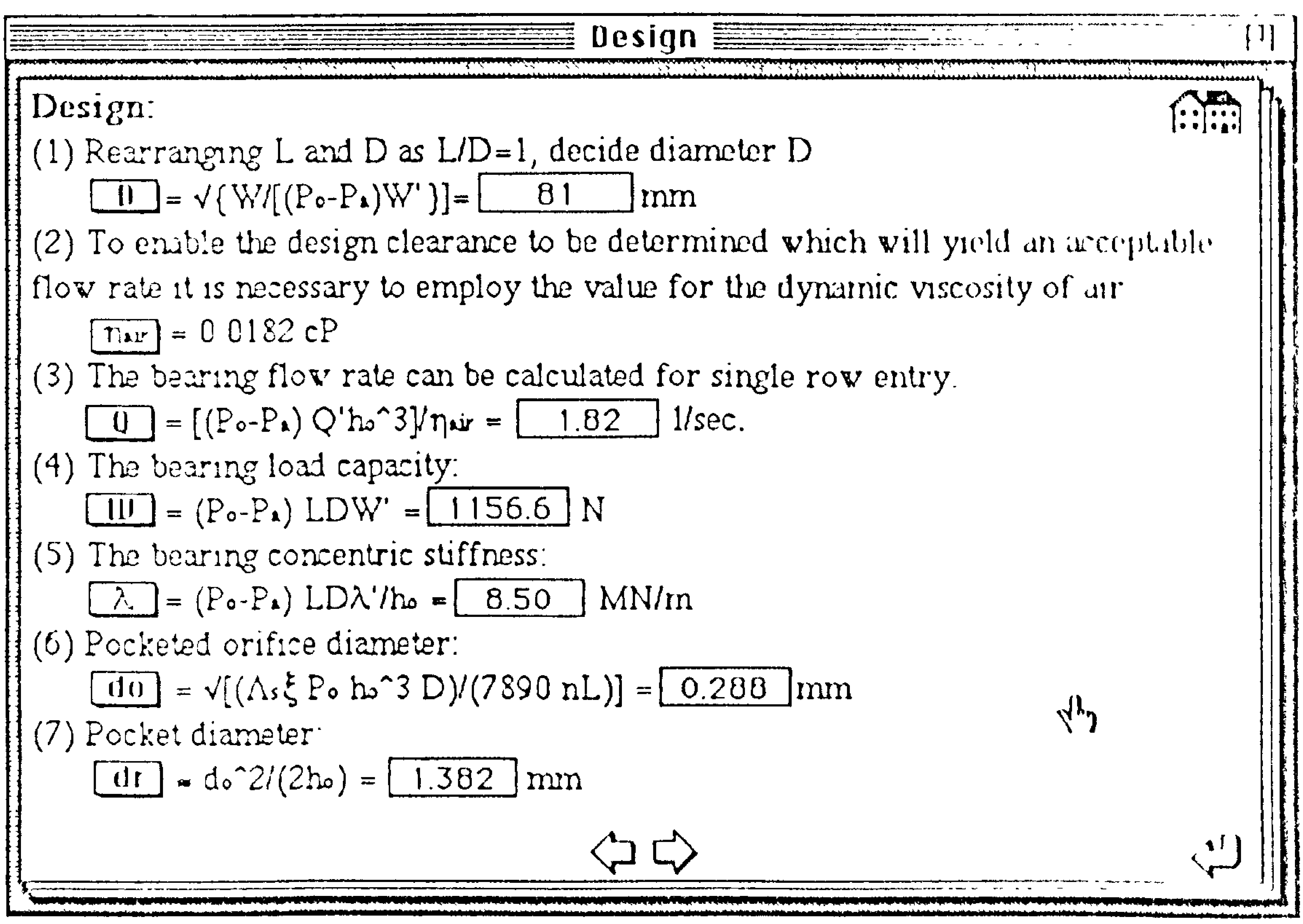
(m)


Design
Design of Aerostatic Journal Bearings
(Click an icon to enter the the bearing design procedure)
Pocketed Orifice
Slot Entry
Annular Orifice
Porous Wall

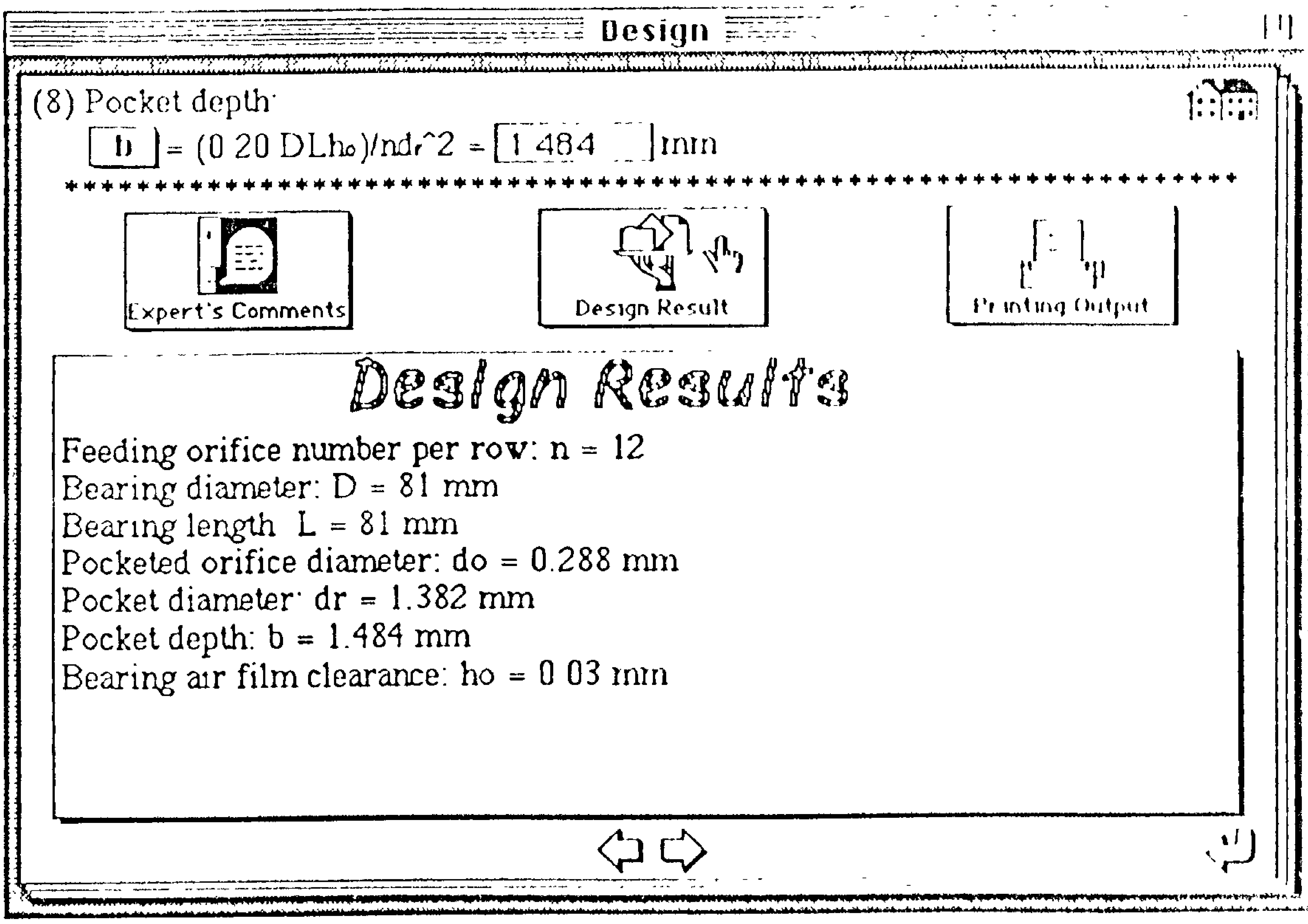
(n)


Design
Design of an aerostatic cylindrical journal bearing with pocketed orifices
Please input values of the bearing parameters. During input, the system will give advice. When finished, please click 'Design' to enter the design procedure.
1. Basic parametrs constrained by machine design:
External load W ≤ 1350 N
Bearing length L = 70 mm
Bearing diameter D = 70 mm
2. Selected basic parameters:
Single or double row enrty: N = 2
Eccentricity ratio ε = 0.5
Number of entry orifices per row: n = 12
Supply pressure Po/Pa = 6
Gauge pressure ratio Kgo = 0.4
Air film clearance ho = 0.03 mm
Design
Browse...
About...
Drawing

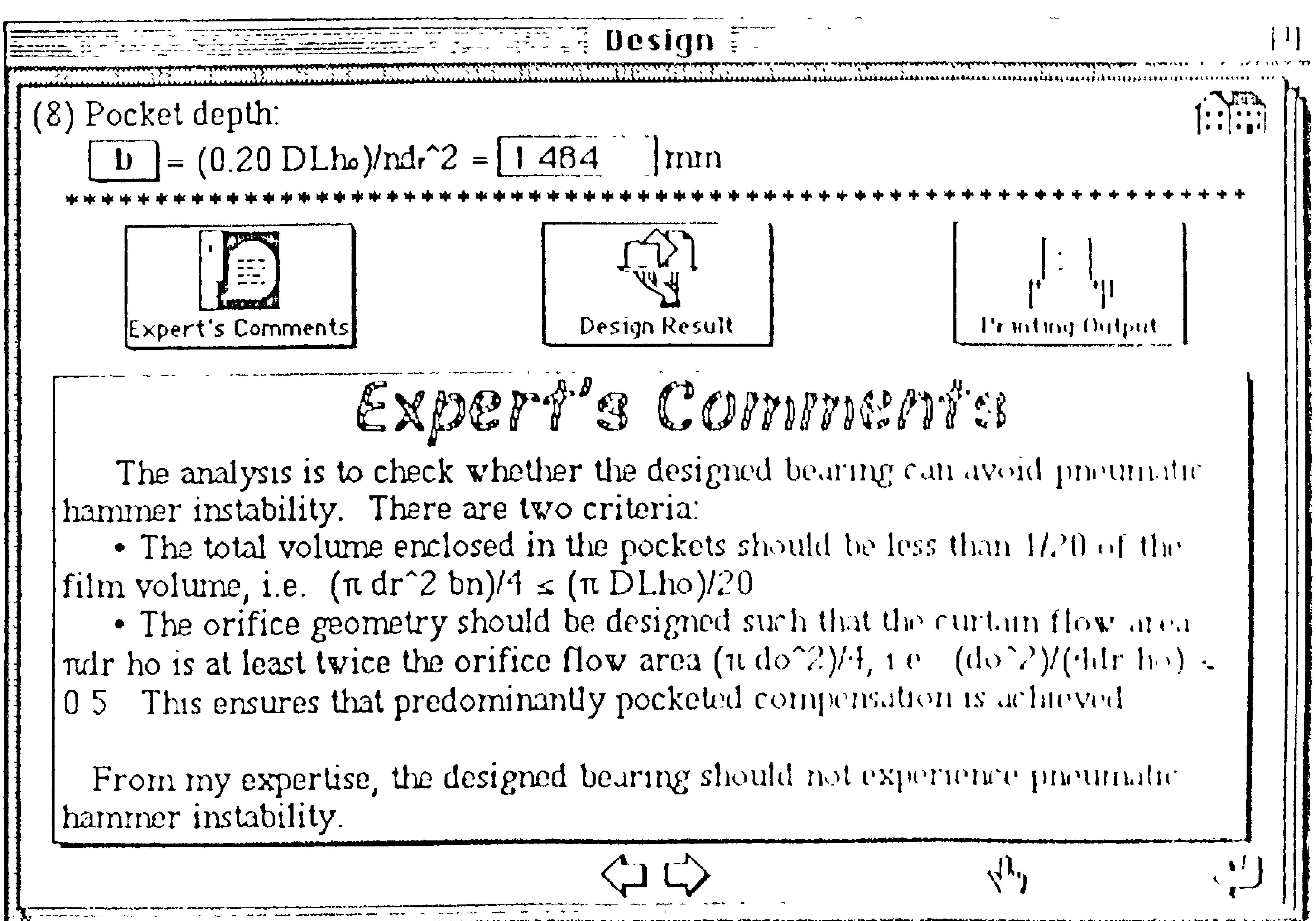
(o)


Design
Design:
(1) Rearranging L and D as L/D=1, decide diameter D
D = √{W/[(Po-Pa)W']}= 81 mm
(2) To enable the design clearance to be determined which will yield an acceptable flow rate it is necessary to employ the value for the dynamic viscosity of air
ηair = 0.0182 cP
(3) The bearing flow rate can be calculated for single row entry.
Q = [(Po-Pa) Q'ho^3]/ηair = 1.82 l/sec.
(4) The bearing load capacity:
W = (Po-Pa) LDW' = 1156.6 N
(5) The bearing concentric stiffness:
λ = (Po-Pa) LDλ'/ho = 8.50 MN/m
(6) Pocketed orifice diameter:
do = √[(Asξ Po ho^3 D)/(7890 nL)] = 0.288 mm
(7) Pocket diameter:
dr = do^2/(2ho) = 1.382 mm

(p)

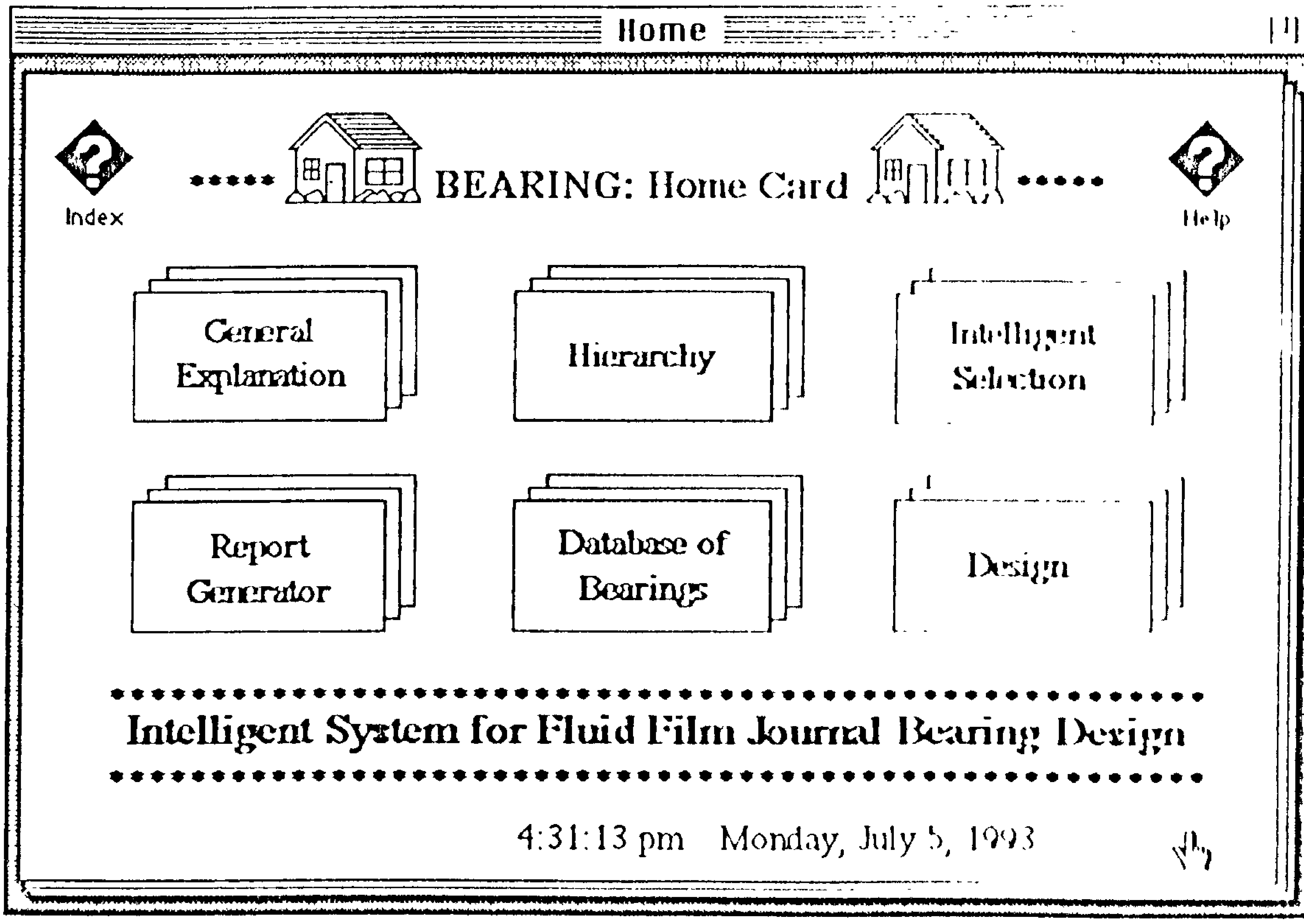

Design
(8) Pocket depth:
b = (0.20 DLho)/ndr^2 = 1.484 mm
Expert's Comments
Design Result
Printing Output
Design Results
Feeding orifice number per row: n = 12
Bearing diameter: D = 81 mm
Bearing length L = 81 mm
Pocketed orifice diameter: do = 0.288 mm
Pocket diameter: dr = 1.382 mm
Pocket depth: b = 1.484 mm
Bearing air film clearance: ho = 0.03 mm

(q)

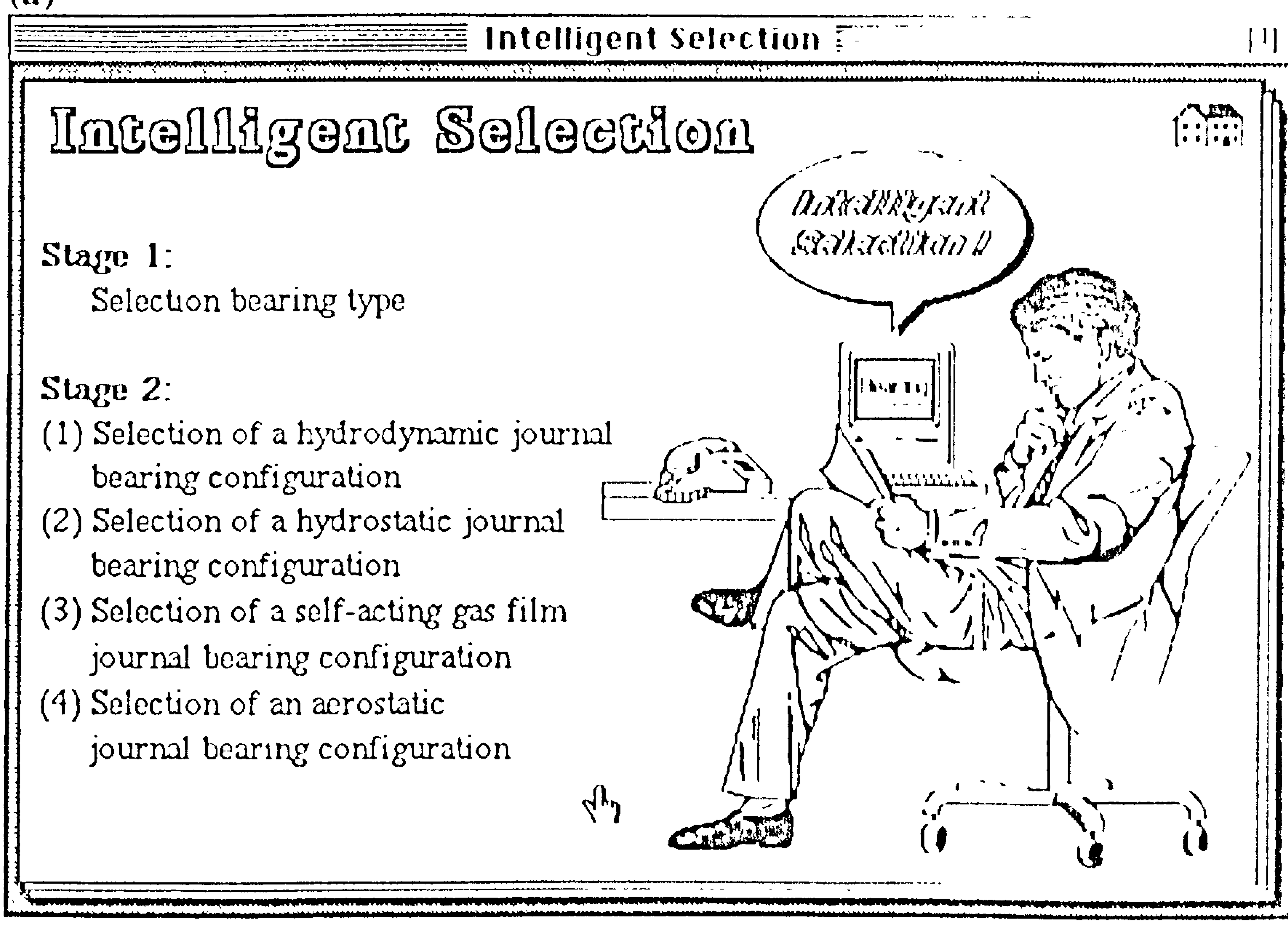

Design
(8) Pocket depth:
b = (0.20 DLho)/ndr^2 = 1.484 mm
Expert's Comments
Design Result
Printing Output
Expert's Comments
The analysis is to check whether the designed bearing can avoid pneumatic hammer instability. There are two criteria:
• The total volume enclosed in the pockets should be less than 1/20 of the film volume, i.e. (π dr^2 bn)/4 ≤ (π DLho)/20
• The orifice geometry should be designed such that the curtain flow area πdr ho is at least twice the orifice flow area (π do^2)/4, i.e. (do^2)/(4dr ho) ≤ 0.5 This ensures that predominantly pocketed compensation is achieved
From my expertise, the designed bearing should not experience pneumatic hammer instability.

(r)

Appendix IV The complete design procedure for a hydrostatic journal bearing with capillary restrictors



(a)



(b)

Intelligent Selection

**** Selection of bearing type ****

Click on the answer which best match your requirements The "Expert" will then interpret your requirements and recommend a bearing type See how you get on

1. Expert: **How severe are the environmental conditions which the bearing must tolerate?**

   (1) High temperature limit

   User: ○ >100 °C ○ 55 °C ◉ 35 °C ○ 25 °C

   (2) Low temperature limit

   User: ○ -20 °C ○ -10 °C ◉ 0 °C ○ 15 °C

   (3) External vibration

   User: ○ Much vibration ◉ Noisy ○ Some ○ No vibration

   (4) Radiation

   User: ○ Much radiation ○ Substantial ○ Some ◉ No radiation

(c)

Intelligent Selection

   (5) Wet and humid conditions

   User: ○ Submerged ○ Wet ◉ Humid ○ Dry

   (6) Dirty and dusty conditions

   User: ○ Very dirty ○ Dirty ◉ Normal ○ Clean

2. Expert: **What is the requirement for the bearing's costs?**

   (1) Running costs

   User: ○ The lower, the better.

   ◉ Low, but the costs of pressurised supply can be accepted

   ○ No requirement.

   (2) Production costs

   User: ○ Low costs ◉ Normal costs ○ No requirement

3. Expert: **What is the requirement for the bearing's following performance?**

   (1) Radial motion accuracy

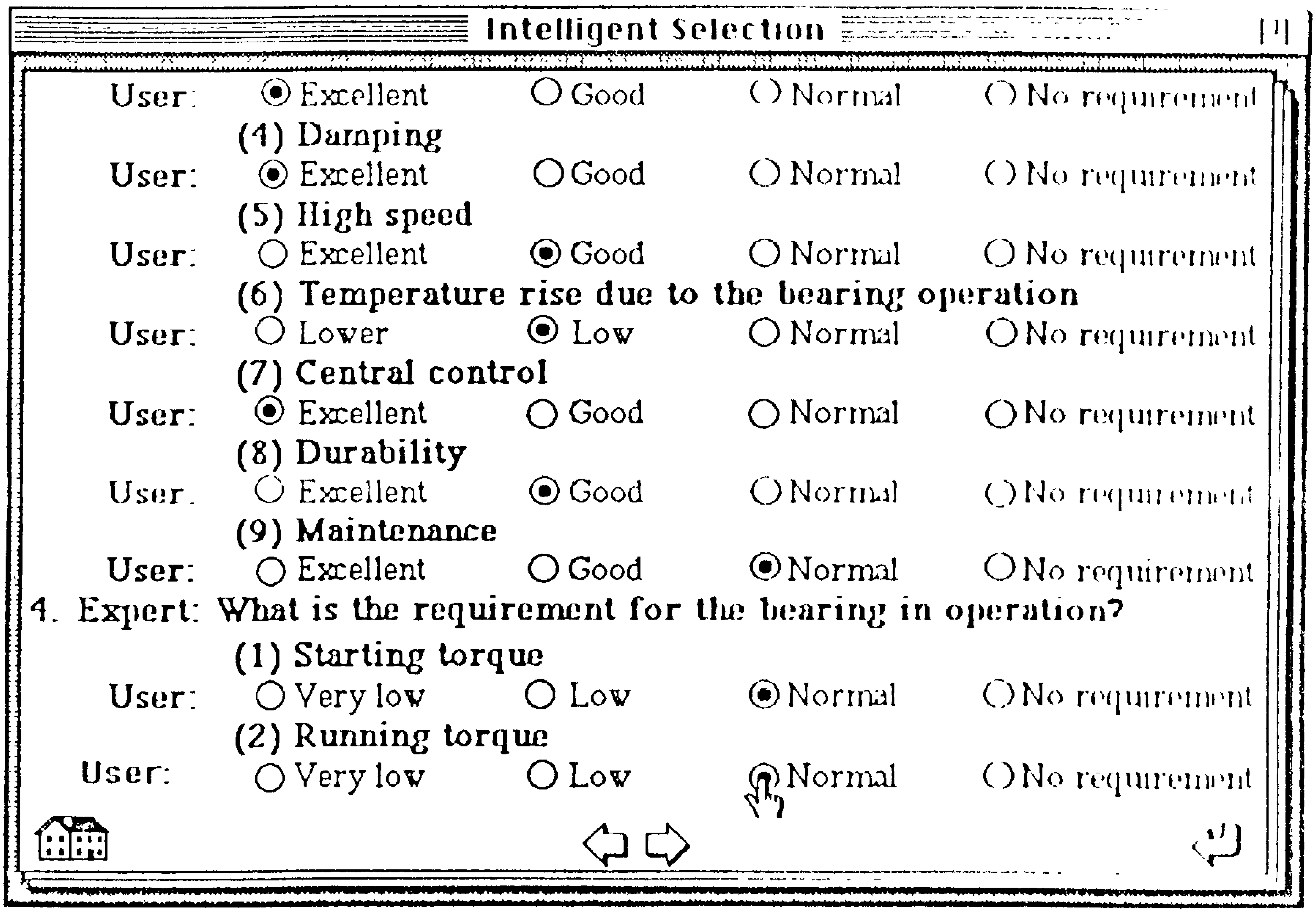
   User: ◉ Excellent ○ Good ○ Normal ○ No requirement

   (2) Load carrying capacity in relation to size

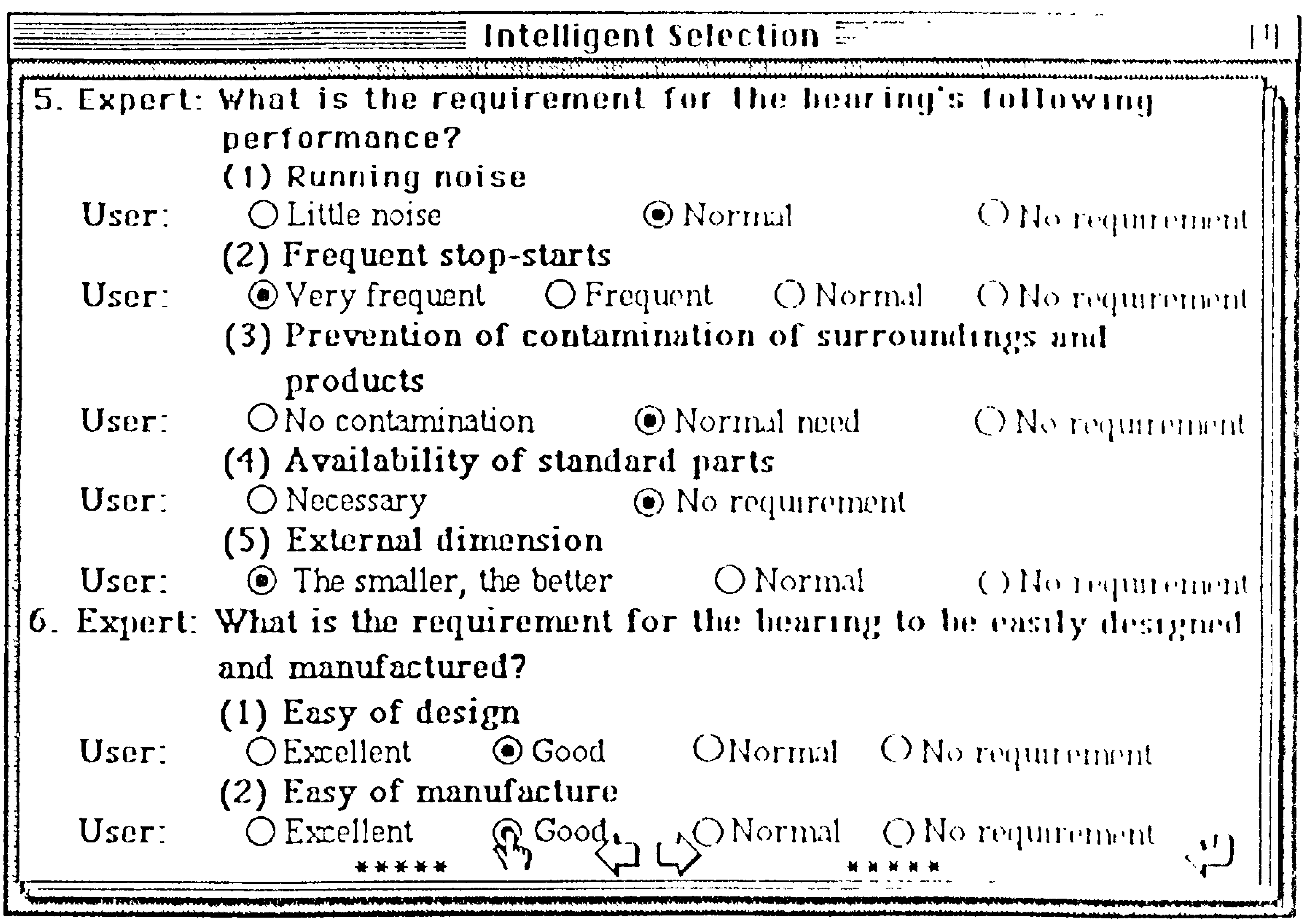
   User: ◉ Excellent ○ Good ○ Normal ○ No requirement

   (3) Stiffness in relation to size

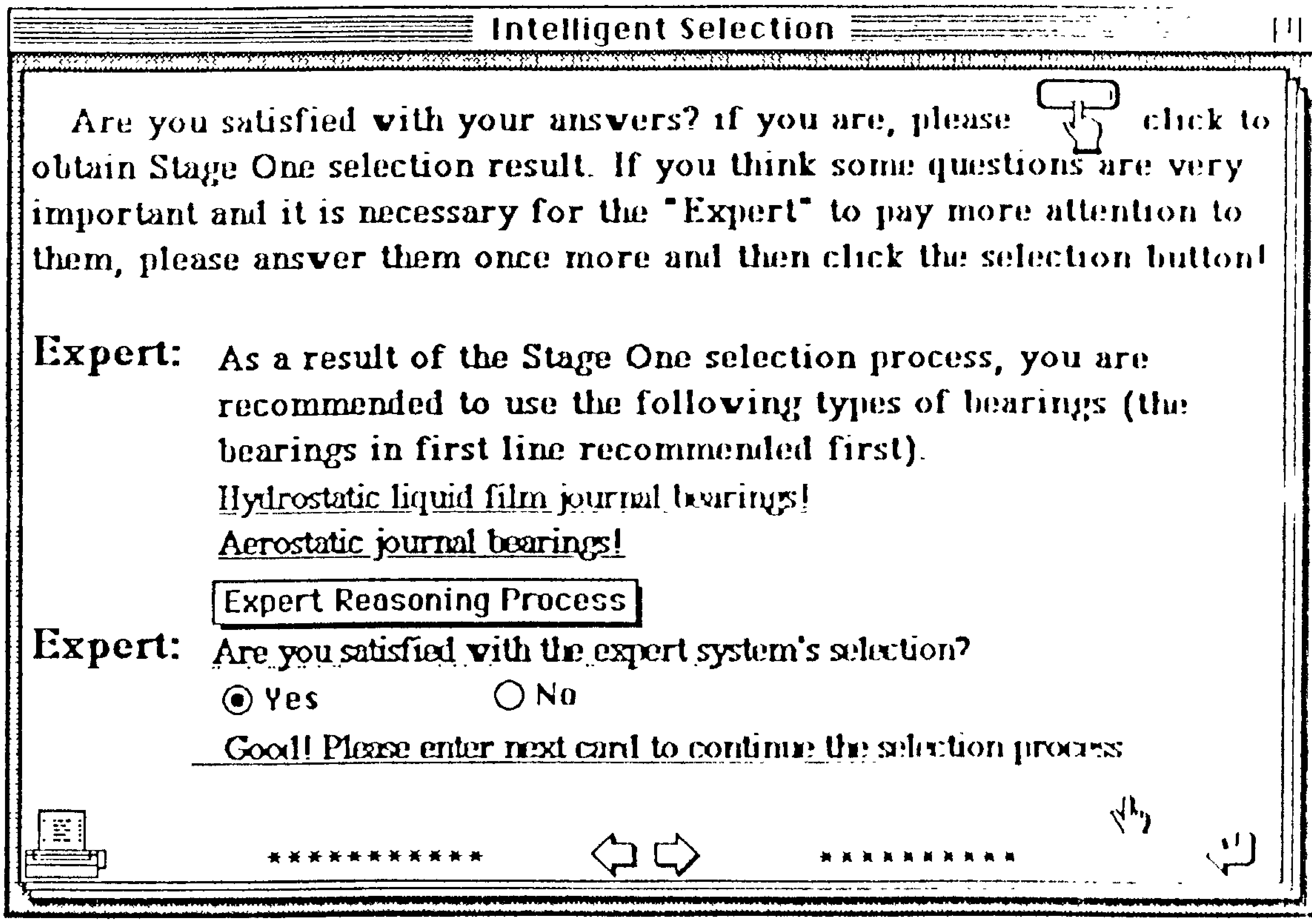
(d)


Intelligent Selection
User: ⦿ Excellent ○ Good ○ Normal ○ No requirement
(4) Damping
User: ⦿ Excellent ○ Good ○ Normal ○ No requirement
(5) High speed
User: ○ Excellent ⦿ Good ○ Normal ○ No requirement
(6) Temperature rise due to the bearing operation
User: ○ Lower ⦿ Low ○ Normal ○ No requirement
(7) Central control
User: ⦿ Excellent ○ Good ○ Normal ○ No requirement
(8) Durability
User: ○ Excellent ⦿ Good ○ Normal ○ No requirement
(9) Maintenance
User: ○ Excellent ○ Good ⦿ Normal ○ No requirement
4. Expert: What is the requirement for the bearing in operation?
(1) Starting torque
User: ○ Very low ○ Low ⦿ Normal ○ No requirement
(2) Running torque
User: ○ Very low ○ Low ○ Normal ○ No requirement

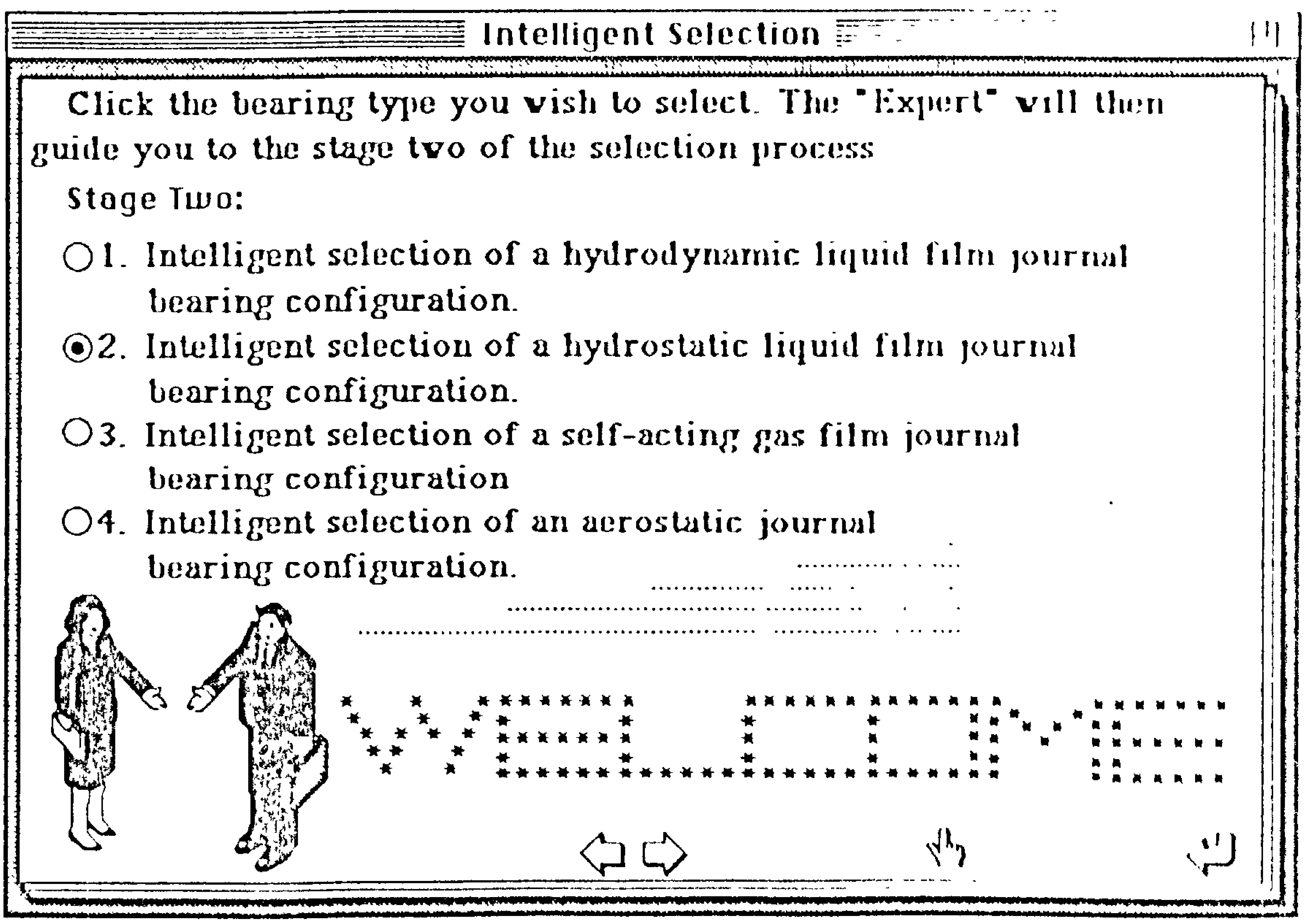
(e)


Intelligent Selection
5. Expert: What is the requirement for the bearing's following performance?
(1) Running noise
User: ○ Little noise ⦿ Normal ○ No requirement
(2) Frequent stop-starts
User: ⦿ Very frequent ○ Frequent ○ Normal ○ No requirement
(3) Prevention of contamination of surroundings and products
User: ○ No contamination ⦿ Normal need ○ No requirement
(4) Availability of standard parts
User: ○ Necessary ⦿ No requirement
(5) External dimension
User: ⦿ The smaller, the better ○ Normal ○ No requirement
6. Expert: What is the requirement for the bearing to be easily designed and manufactured?
(1) Easy of design
User: ○ Excellent ⦿ Good ○ Normal ○ No requirement
(2) Easy of manufacture
User: ○ Excellent ○ Good ○ Normal ○ No requirement
*****
*****

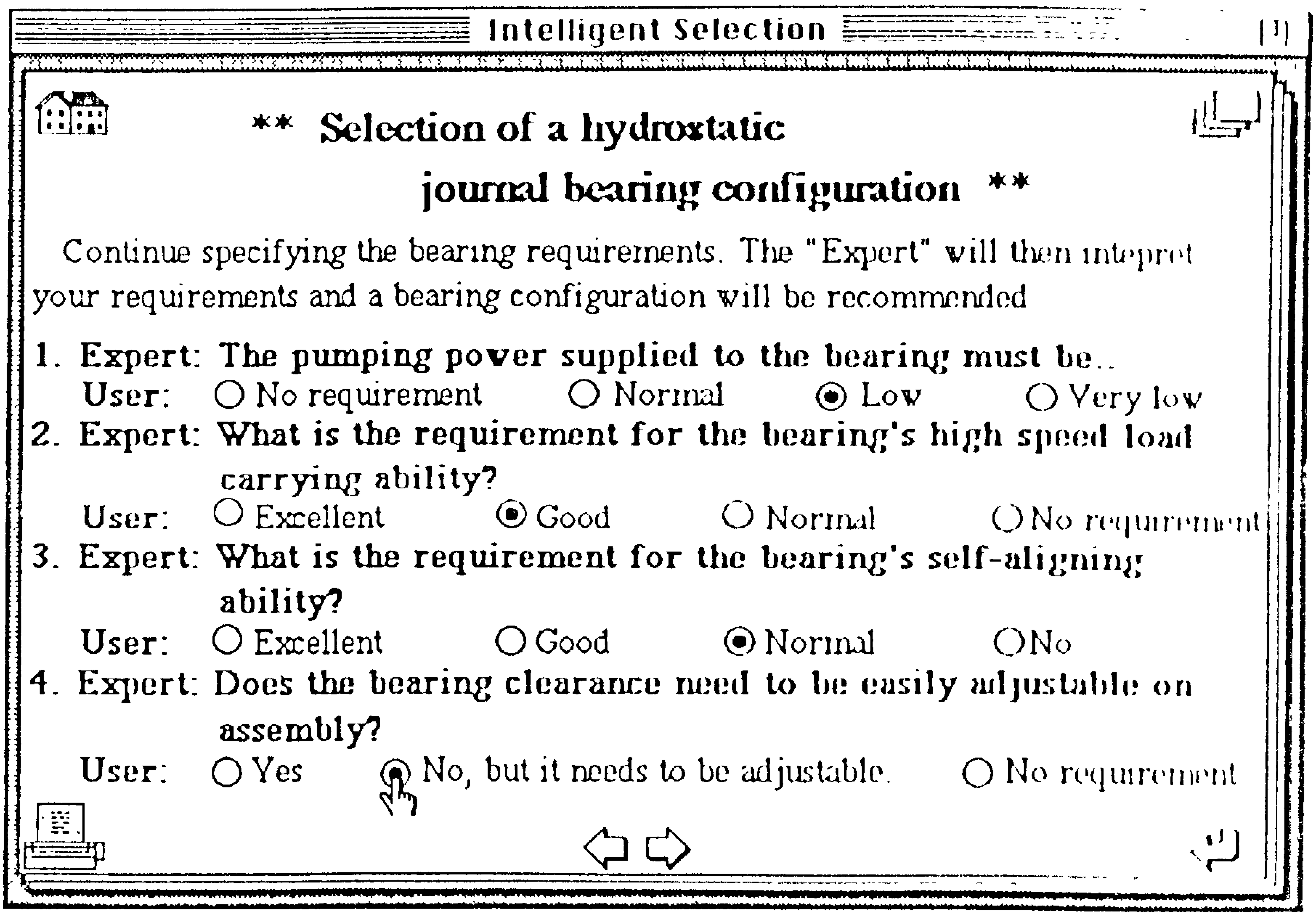
(f)


Intelligent Selection
Are you satisfied with your answers? if you are, please click to obtain Stage One selection result. If you think some questions are very important and it is necessary for the "Expert" to pay more attention to them, please answer them once more and then click the selection button!
Expert: As a result of the Stage One selection process, you are recommended to use the following types of bearings (the bearings in first line recommended first).
Hydrostatic liquid film journal bearings!
Aerostatic journal bearings!
Expert Reasoning Process
Expert: Are you satisfied with the expert system's selection?
Yes
No
Good! Please enter next card to continue the selection process
*********** **********

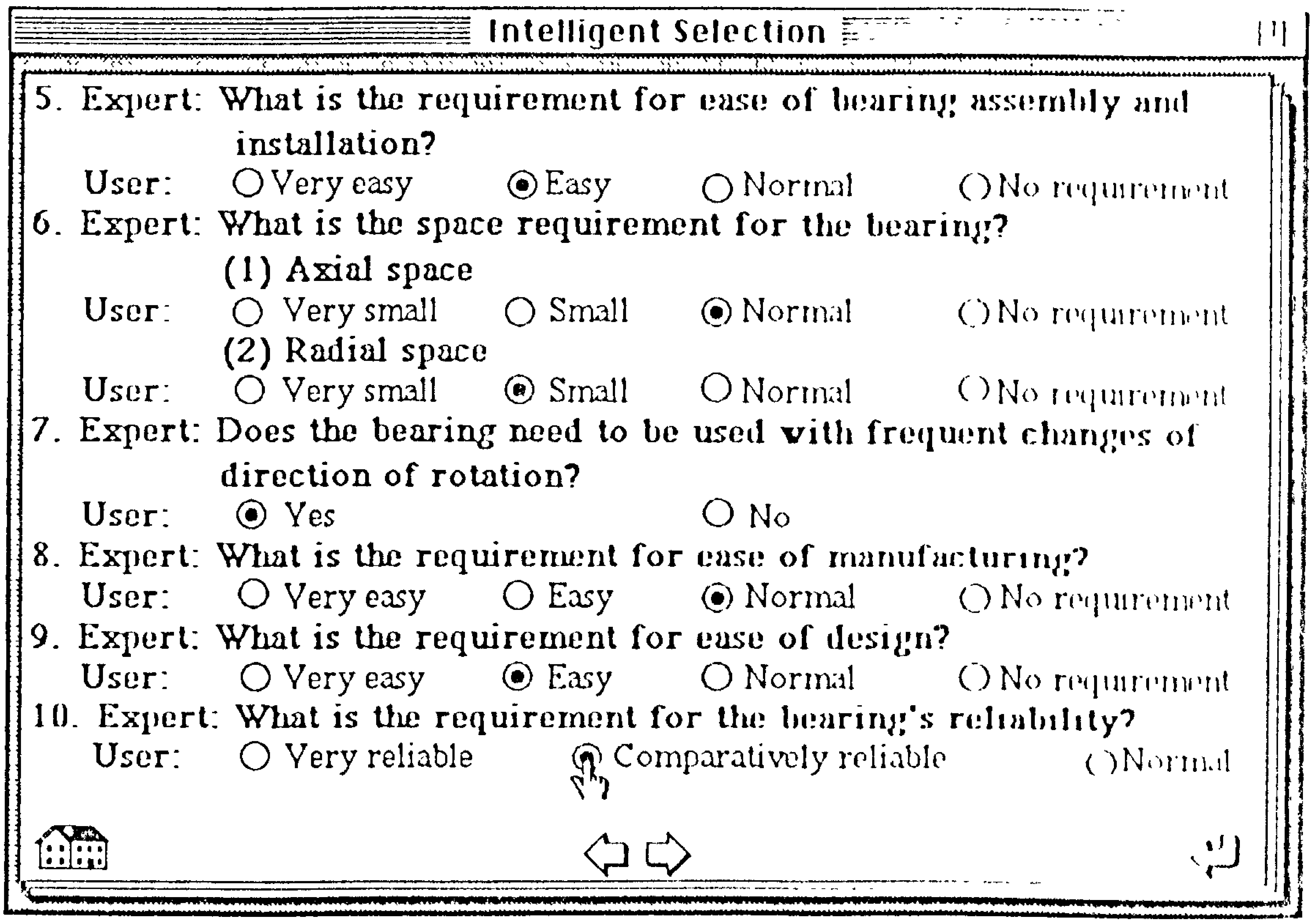
(g)


Intelligent Selection
Click the bearing type you wish to select. The "Expert" will then guide you to the stage two of the selection process
Stage Two:
1. Intelligent selection of a hydrodynamic liquid film journal bearing configuration.
2. Intelligent selection of a hydrostatic liquid film journal bearing configuration.
3. Intelligent selection of a self-acting gas film journal bearing configuration
4. Intelligent selection of an aerostatic journal bearing configuration.
WELCOME

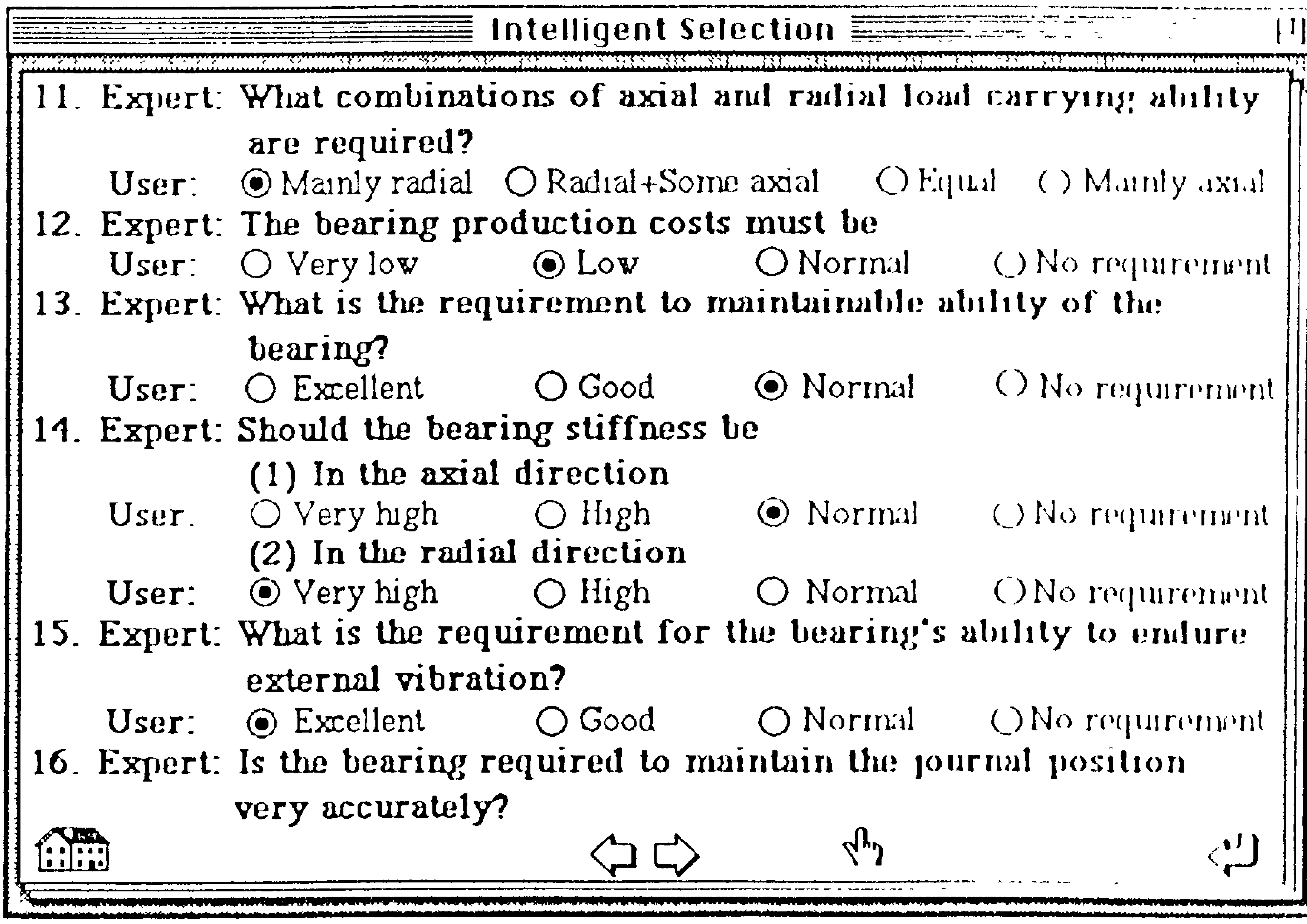
(h)


Intelligent Selection
** Selection of a hydrostatic journal bearing configuration **
Continue specifying the bearing requirements. The "Expert" will then interpret your requirements and a bearing configuration will be recommended
1. Expert: The pumping power supplied to the bearing must be..
User: No requirement Normal Low Very low
2. Expert: What is the requirement for the bearing's high speed load carrying ability?
User: Excellent Good Normal No requirement
3. Expert: What is the requirement for the bearing's self-aligning ability?
User: Excellent Good Normal No
4. Expert: Does the bearing clearance need to be easily adjustable on assembly?
User: Yes No, but it needs to be adjustable. No requirement

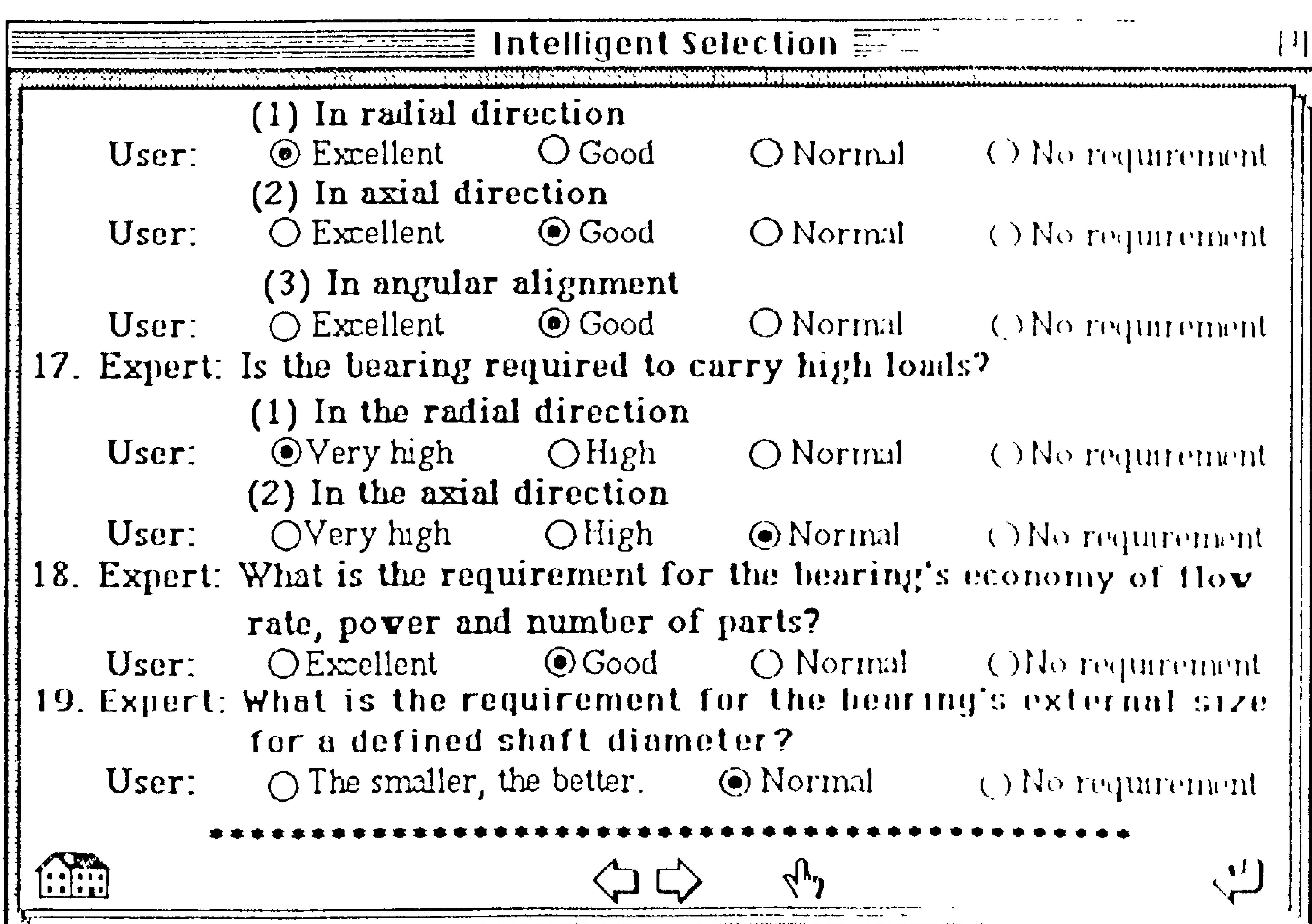
(i)


Intelligent Selection
5. Expert: What is the requirement for ease of bearing assembly and installation?
User: Very easy Easy Normal No requirement
6. Expert: What is the space requirement for the bearing?
(1) Axial space
User: Very small Small Normal No requirement
(2) Radial space
User: Very small Small Normal No requirement
7. Expert: Does the bearing need to be used with frequent changes of direction of rotation?
User: Yes No
8. Expert: What is the requirement for ease of manufacturing?
User: Very easy Easy Normal No requirement
9. Expert: What is the requirement for ease of design?
User: Very easy Easy Normal No requirement
10. Expert: What is the requirement for the bearing's reliability?
User: Very reliable Comparatively reliable Normal

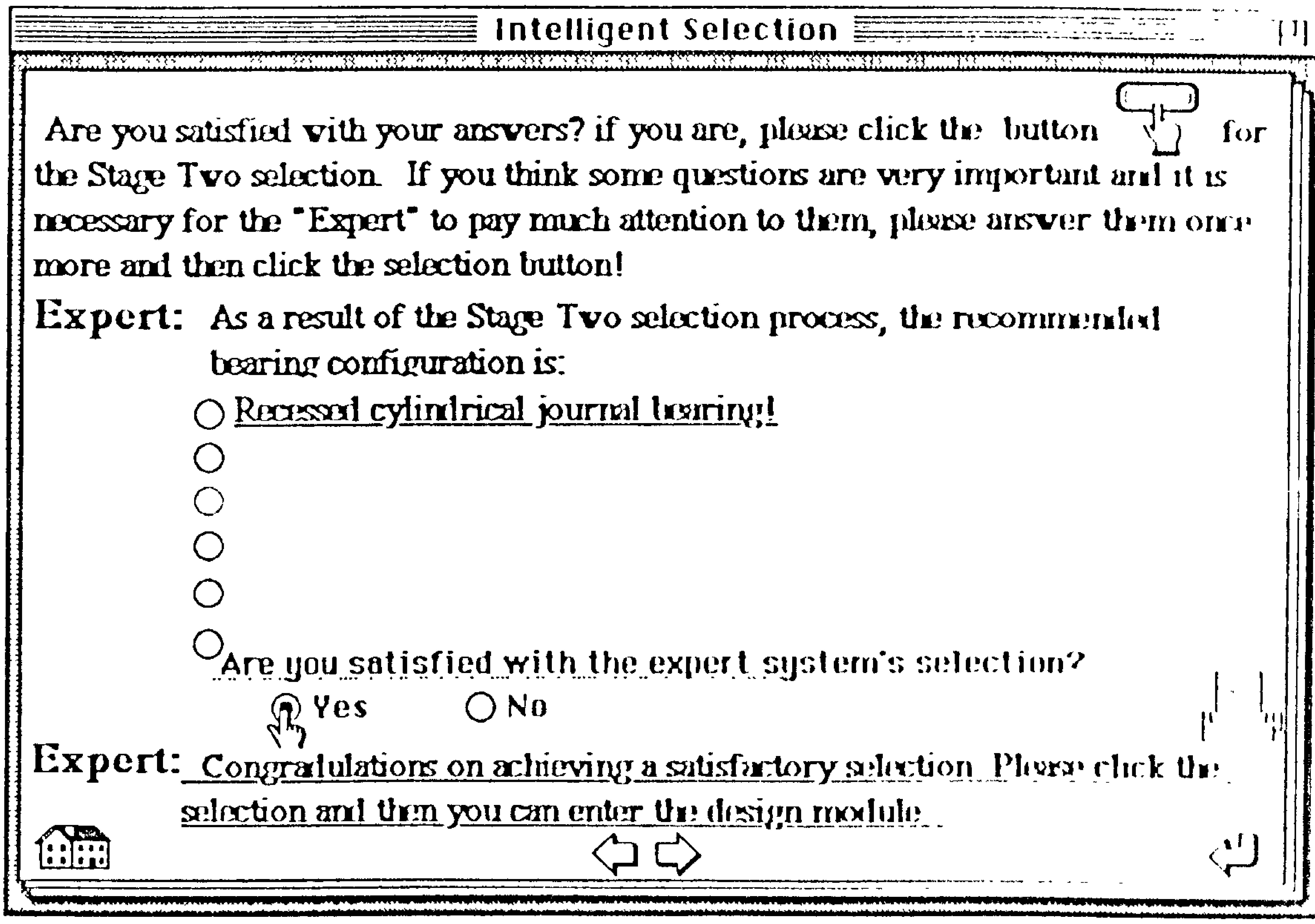
(j)


Intelligent Selection
11. Expert: What combinations of axial and radial load carrying ability are required?
User: ◉ Mainly radial ○ Radial+Some axial ○ Equal ○ Mainly axial
12. Expert: The bearing production costs must be
User: ○ Very low ◉ Low ○ Normal ○ No requirement
13. Expert: What is the requirement to maintainable ability of the bearing?
User: ○ Excellent ○ Good ◉ Normal ○ No requirement
14. Expert: Should the bearing stiffness be
(1) In the axial direction
User: ○ Very high ○ High ◉ Normal ○ No requirement
(2) In the radial direction
User: ◉ Very high ○ High ○ Normal ○ No requirement
15. Expert: What is the requirement for the bearing's ability to endure external vibration?
User: ◉ Excellent ○ Good ○ Normal ○ No requirement
16. Expert: Is the bearing required to maintain the journal position very accurately?

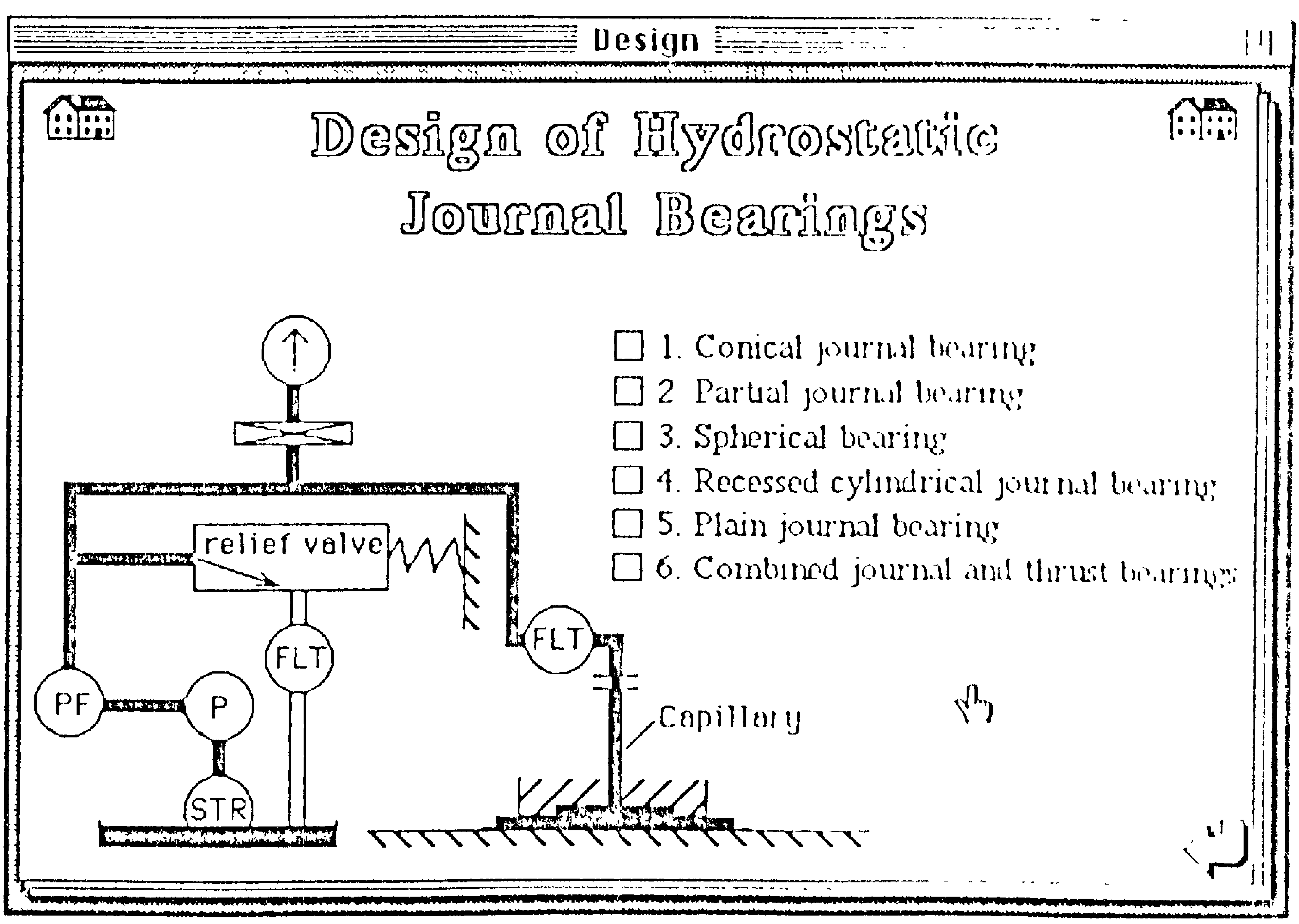
(k)


Intelligent Selection
(1) In radial direction
User: ◉ Excellent ○ Good ○ Normal ○ No requirement
(2) In axial direction
User: ○ Excellent ◉ Good ○ Normal ○ No requirement
(3) In angular alignment
User: ○ Excellent ◉ Good ○ Normal ○ No requirement
17. Expert: Is the bearing required to carry high loads?
(1) In the radial direction
User: ◉ Very high ○ High ○ Normal ○ No requirement
(2) In the axial direction
User: ○ Very high ○ High ◉ Normal ○ No requirement
18. Expert: What is the requirement for the bearing's economy of flow rate, power and number of parts?
User: ○ Excellent ◉ Good ○ Normal ○ No requirement
19. Expert: What is the requirement for the bearing's external size for a defined shaft diameter?
User: ○ The smaller, the better. ◉ Normal ○ No requirement

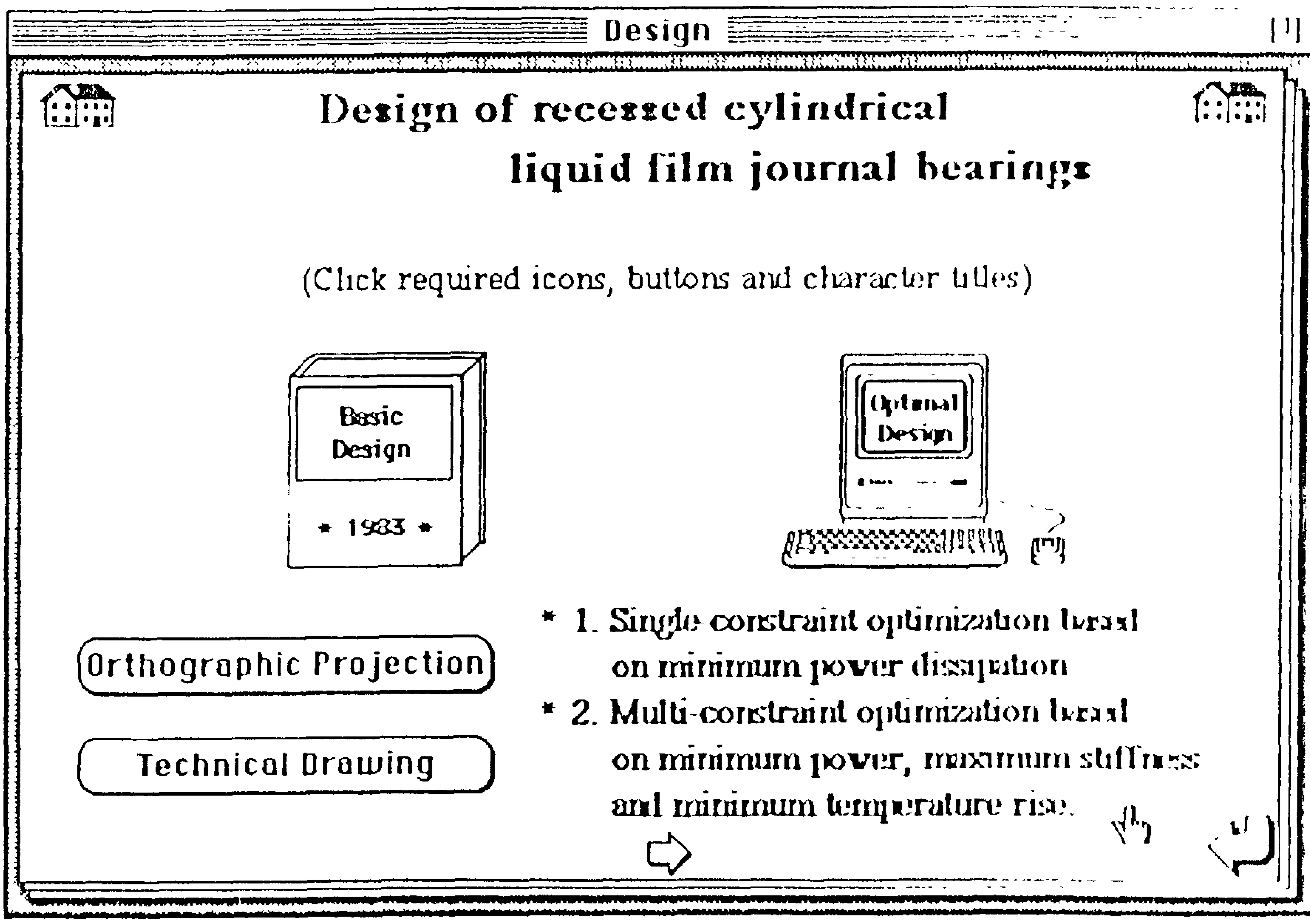
(l)


Intelligent Selection
Are you satisfied with your answers? if you are, please click the button for the Stage Two selection. If you think some questions are very important and it is necessary for the "Expert" to pay much attention to them, please answer them once more and then click the selection button!
Expert: As a result of the Stage Two selection process, the recommended bearing configuration is:
Recessed cylindrical journal bearing!
Are you satisfied with the expert system's selection?
Yes
No
Expert: Congratulations on achieving a satisfactory selection. Please click the selection and then you can enter the design module.

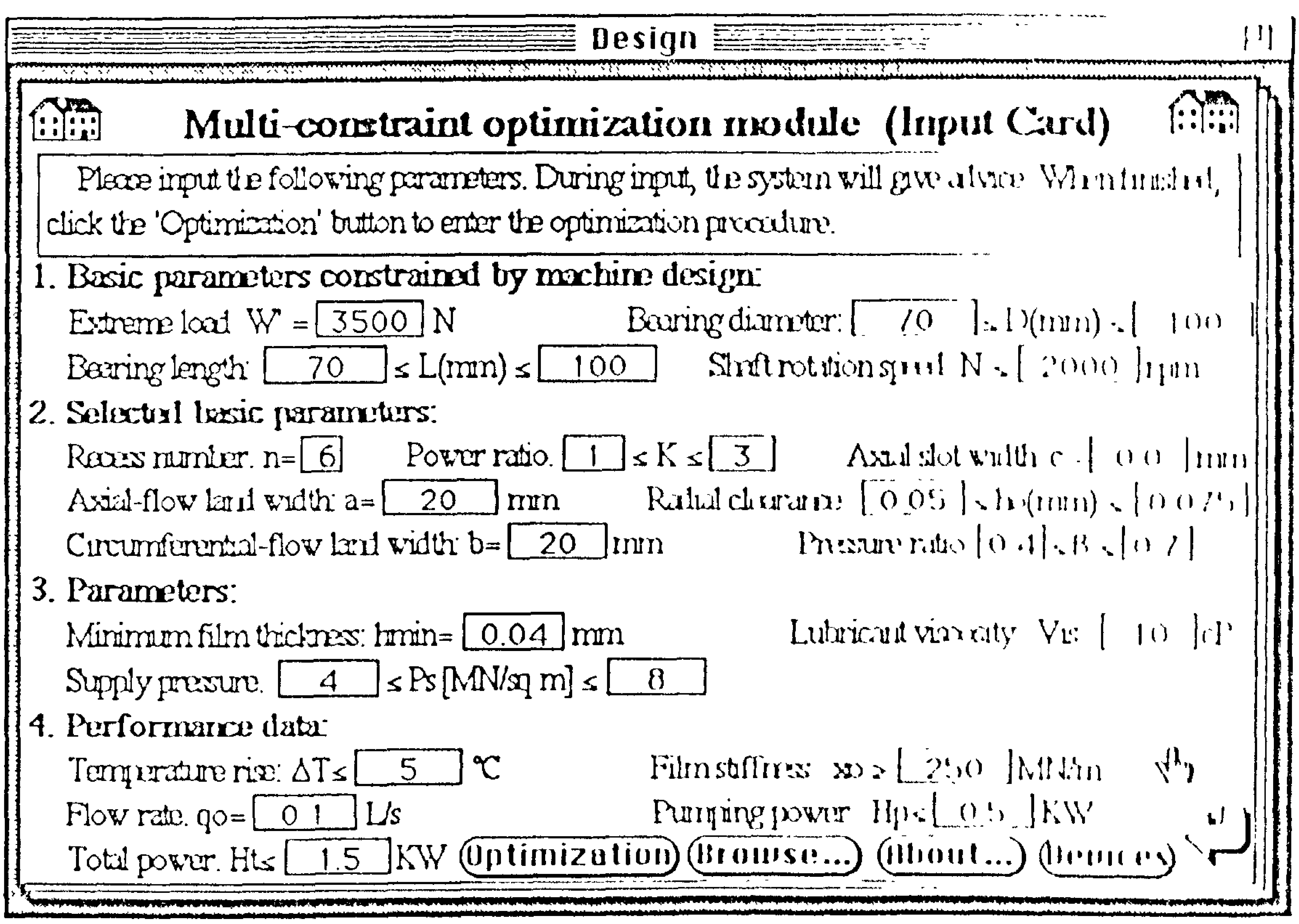
(m)


Design
Design of Hydrostatic Journal Bearings
1. Conical journal bearing
2. Partial journal bearing
3. Spherical bearing
4. Recessed cylindrical journal bearing
5. Plain journal bearing
6. Combined journal and thrust bearings
relief valve
FLT
FLT
PF
P
STR
Capillary

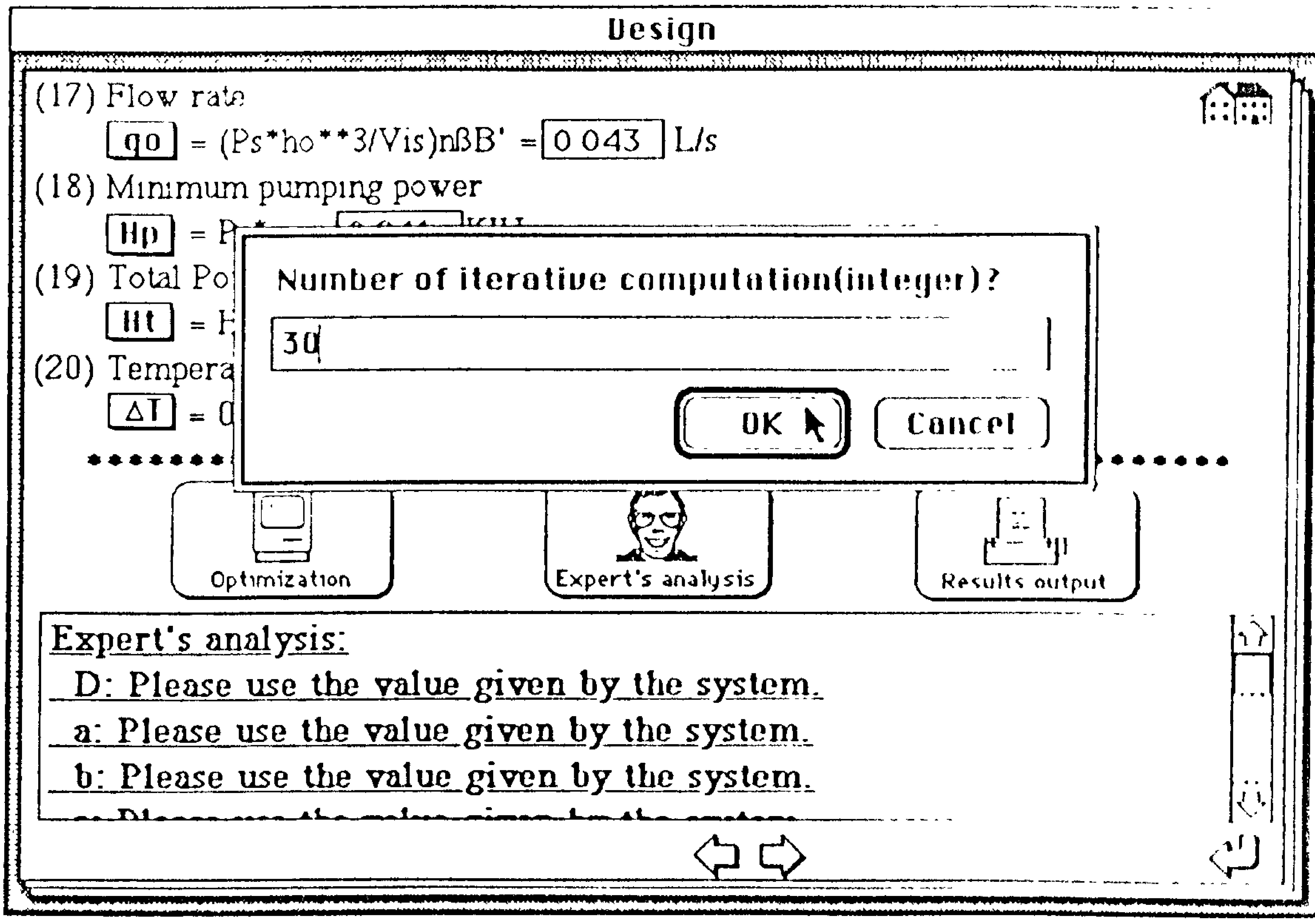
(n)


Design
Design of recessed cylindrical
liquid film journal bearings
(Click required icons, buttons and character titles)
Basic
Design
* 1983 *
Optimal
Design
Orthographic Projection
Technical Drawing
* 1. Single-constraint optimization based
on minimum power dissipation
* 2. Multi-constraint optimization based
on minimum power, maximum stiffness
and minimum temperature rise.

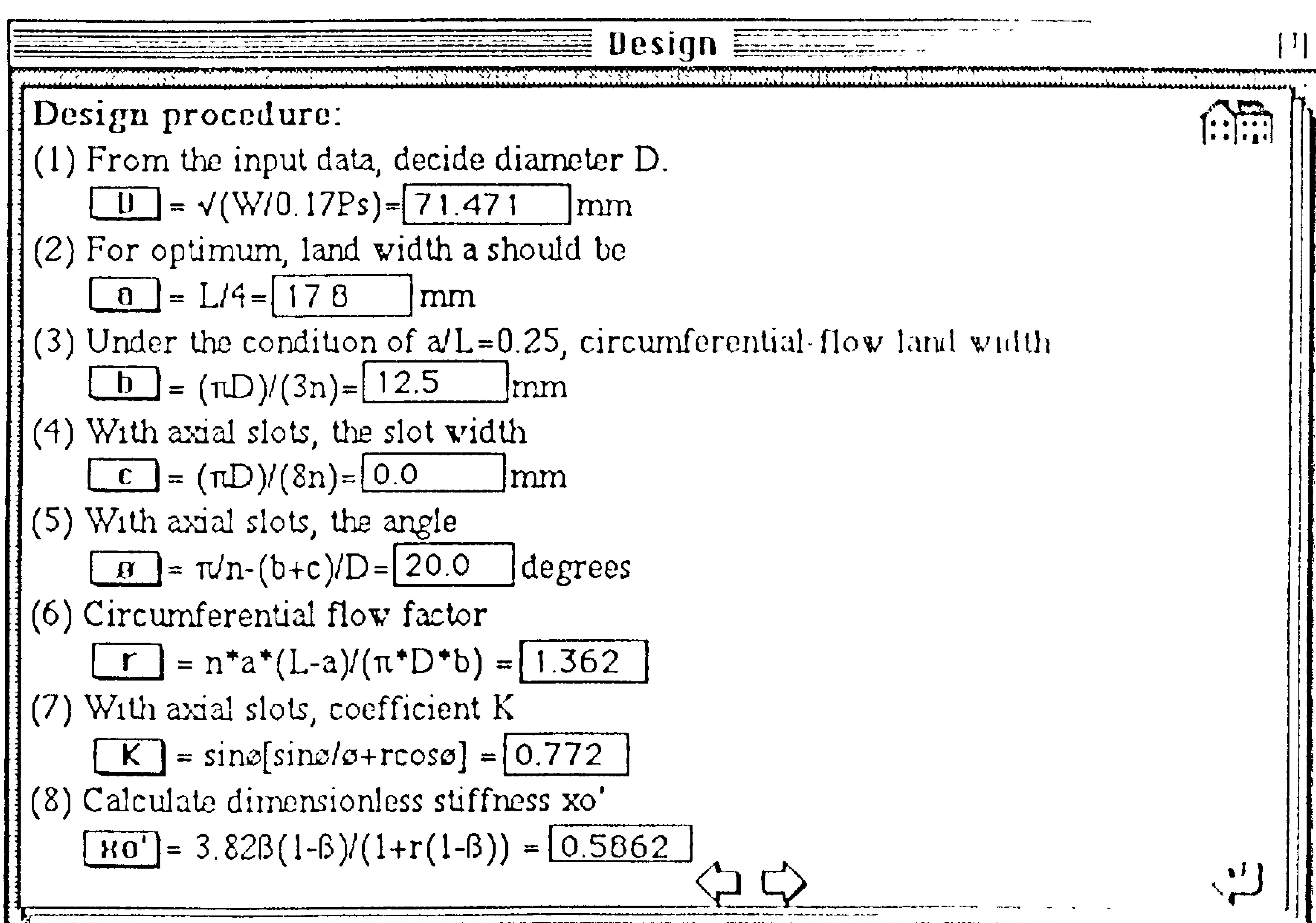
(o)


Design
Multi-constraint optimization module (Input Card)
Please input the following parameters. During input, the system will give advice. When finished,
click the 'Optimization' button to enter the optimization procedure.
1. Basic parameters constrained by machine design:
Extreme load W' = 3500 N
Bearing diameter: 70 ≤ D(mm) ≤ 100
Bearing length: 70 ≤ L(mm) ≤ 100
Shaft rotation speed N ≤ 2000 rpm
2. Selected basic parameters:
Recess number. n= 6
Power ratio. 1 ≤ K ≤ 3
Axial-flow land width: a= 20 mm
Circumferential-flow land width: b= 20 mm
3. Parameters:
Minimum film thickness: hmin= 0.04 mm
Supply pressure. 4 ≤ Ps [MN/sq m] ≤ 8
4. Performance data:
Temperature rise: ΔT≤ 5 °C
Flow rate. qo= 0.1 L/s
Total power. Ht≤ 1.5 KW
Optimization
Browse...
About...

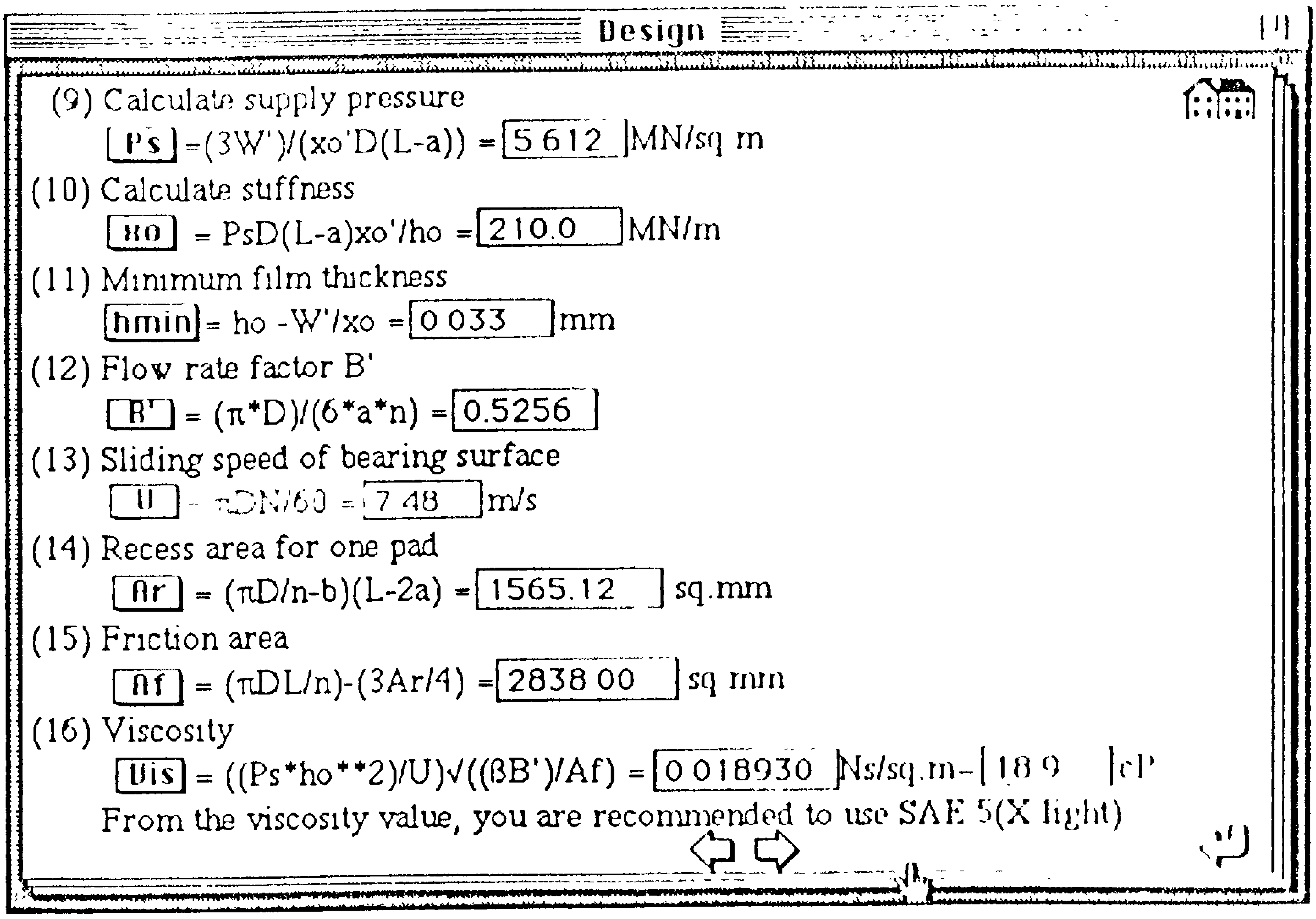
(p)


Design
(17) Flow rate
qo = (Ps*ho**3/Vis)nßB' = 0.043 L/s
(18) Minimum pumping power
Hp
(19) Total Po
Ht
(20) Tempera
ΔT
Number of iterative computation(integer)?
30
OK
Cancel
Optimization
Expert's analysis
Results output
Expert's analysis:
D: Please use the value given by the system.
a: Please use the value given by the system.
b: Please use the value given by the system.

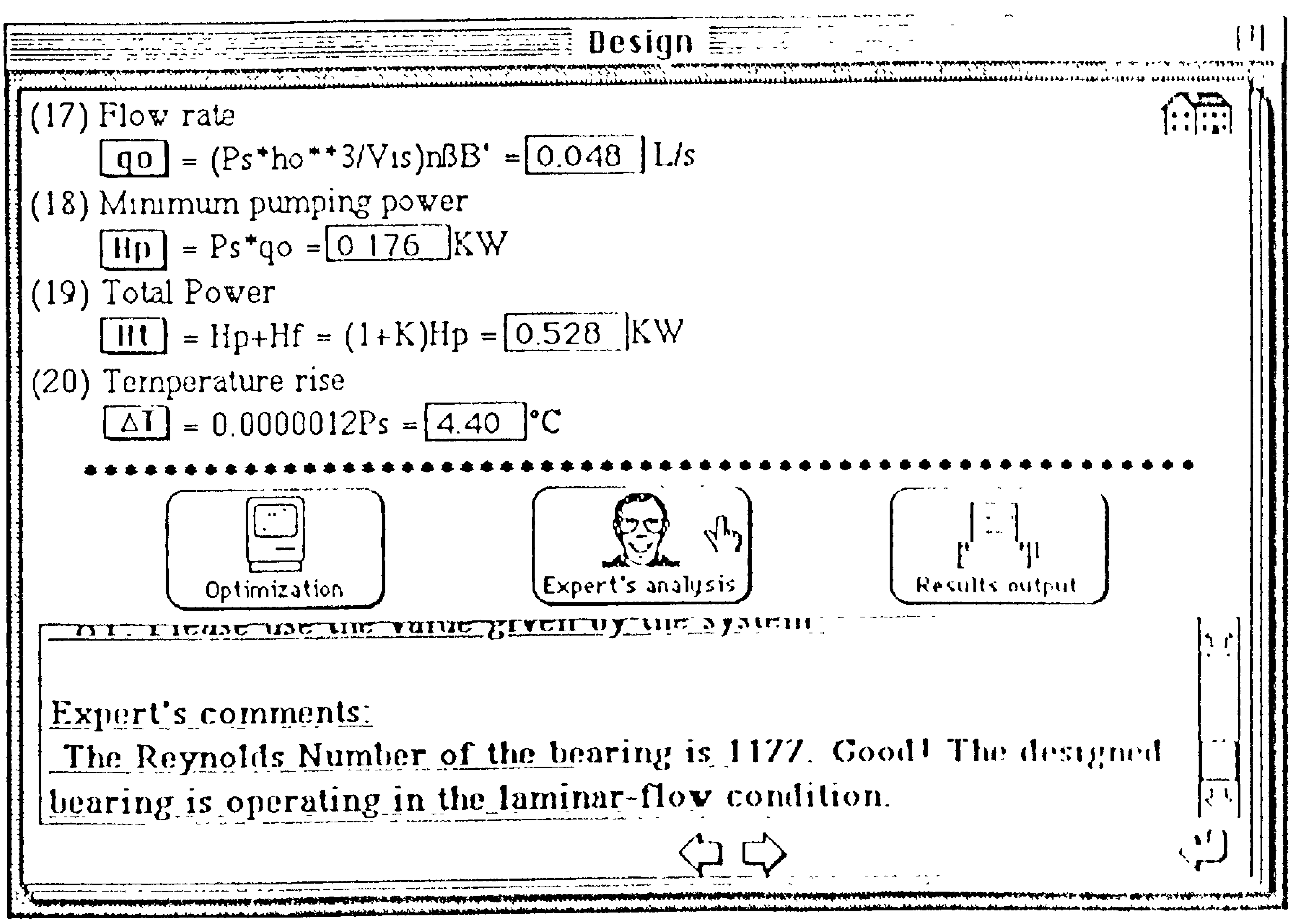
(q)


Design
Design procedure:
(1) From the input data, decide diameter D.
D = √(W/0.17Ps)= 71.471 mm
(2) For optimum, land width a should be
a = L/4= 17.8 mm
(3) Under the condition of a/L=0.25, circumferential-flow land width
b = (πD)/(3n)= 12.5 mm
(4) With axial slots, the slot width
c = (πD)/(8n)= 0.0 mm
(5) With axial slots, the angle
ø = π/n-(b+c)/D= 20.0 degrees
(6) Circumferential flow factor
r = n*a*(L-a)/(π*D*b) = 1.362
(7) With axial slots, coefficient K
K = sinø[sinø/ø+rcosø] = 0.772
(8) Calculate dimensionless stiffness xo'
xo' = 3.82ß(1-ß)/(1+r(1-ß)) = 0.5862

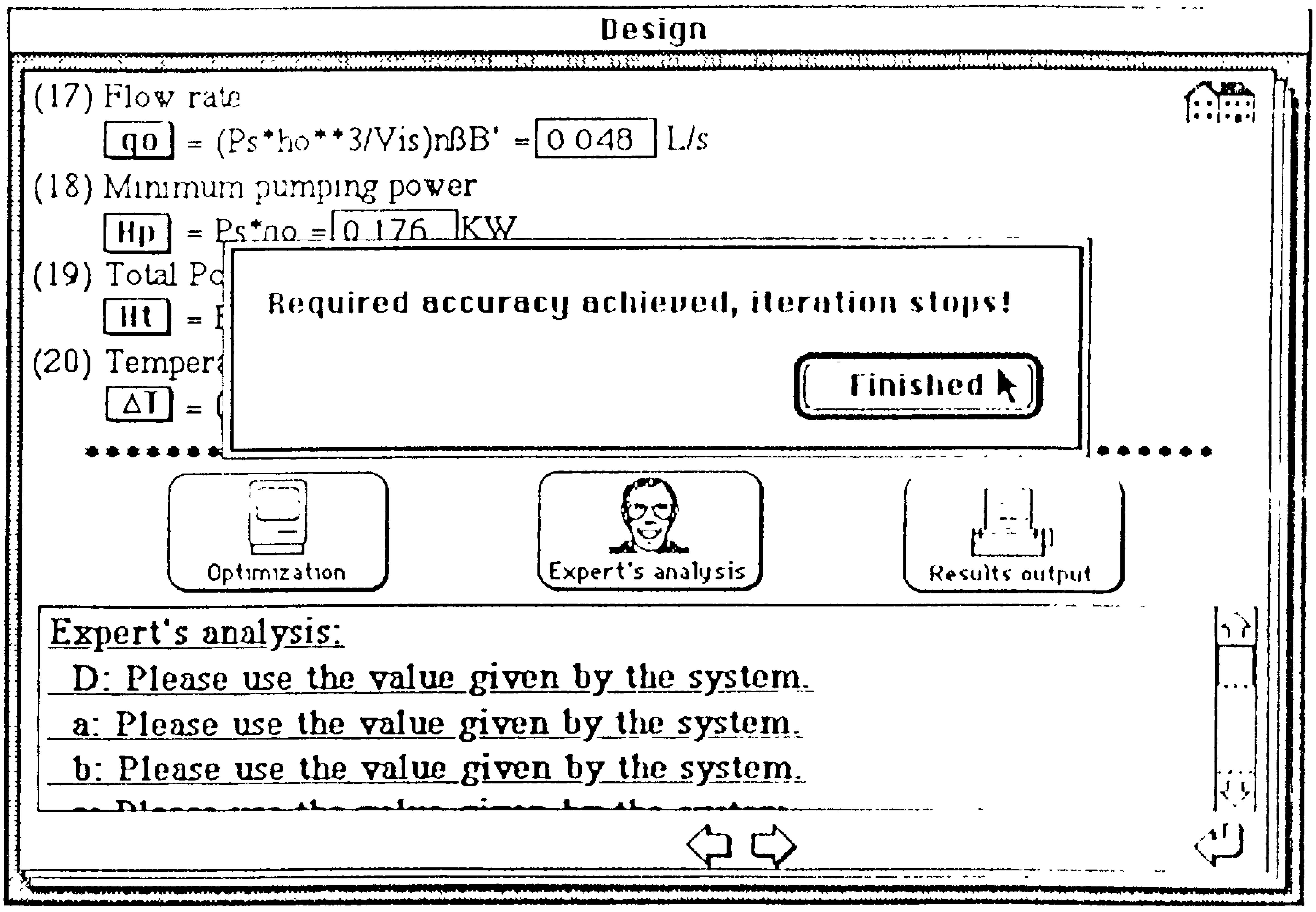
(r)


Design
(9) Calculate supply pressure
Ps =(3W')/(xo'D(L-a)) = 5.612 MN/sq m
(10) Calculate stiffness
ko = PsD(L-a)xo'/ho = 210.0 MN/m
(11) Minimum film thickness
hmin = ho -W'/xo = 0.033 mm
(12) Flow rate factor B'
B' = (π*D)/(6*a*n) = 0.5256
(13) Sliding speed of bearing surface
U = πDN/60 = 7.48 m/s
(14) Recess area for one pad
Ar = (πD/n-b)(L-2a) = 1565.12 sq.mm
(15) Friction area
Af = (πDL/n)-(3Ar/4) = 2838.00 sq mm
(16) Viscosity
Vis = ((Ps*ho**2)/U)√((ßB')/Af) = 0.018930 Ns/sq.m- 18.9 cP
From the viscosity value, you are recommended to use SAE 5(X light)

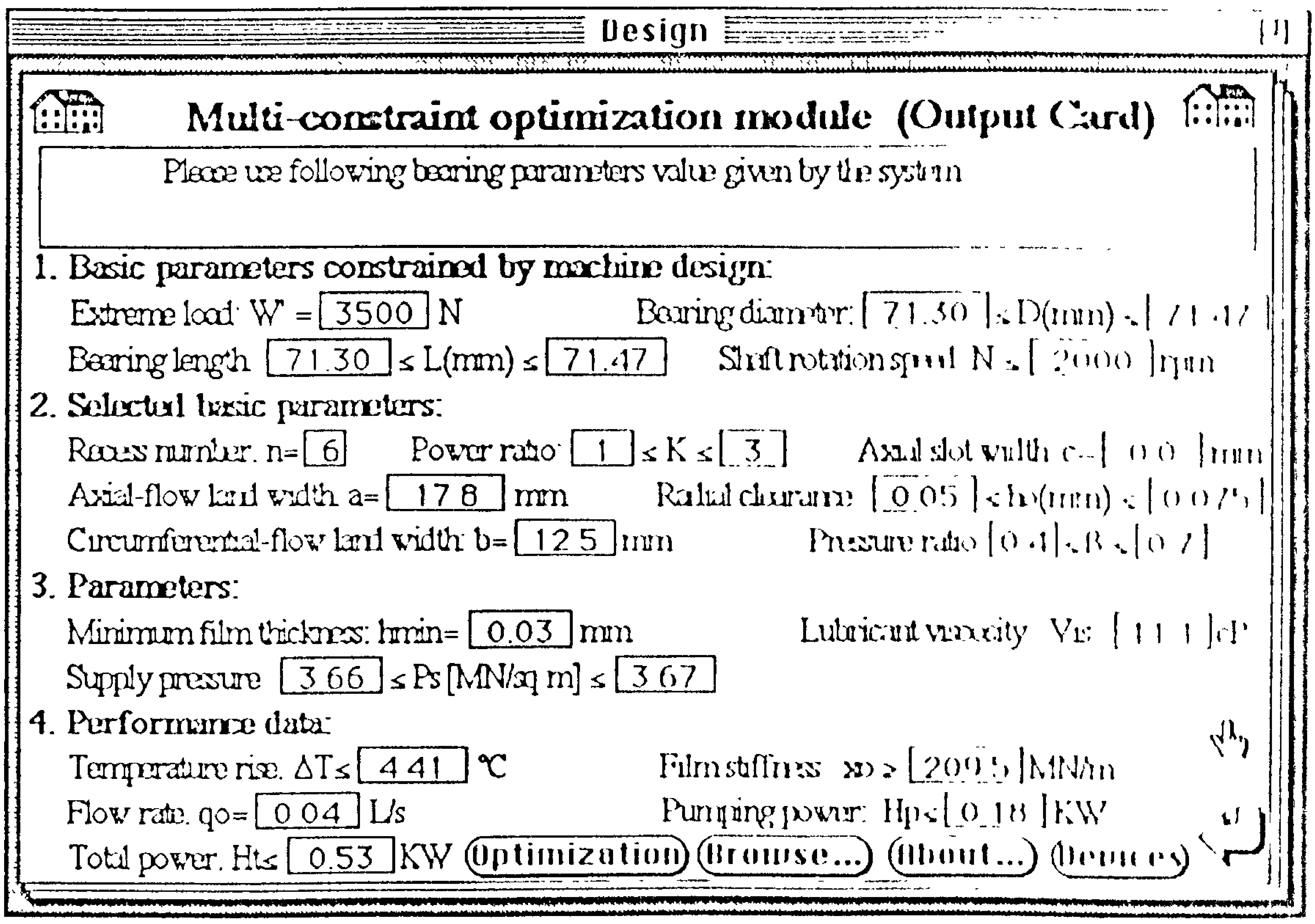
(s)


Design
(17) Flow rate
qo = (Ps*ho**3/Vis)nßB' = 0.048 L/s
(18) Minimum pumping power
Hp = Ps*qo = 0.176 KW
(19) Total Power
Ht = Hp+Hf = (1+K)Hp = 0.528 KW
(20) Temperature rise
ΔT = 0.0000012Ps = 4.40 °C
Optimization
Expert's analysis
Results output
Expert's comments:
The Reynolds Number of the bearing is 1177. Good! The designed bearing is operating in the laminar-flow condition.

(t)


Design
(17) Flow rate
qo = (Ps*ho**3/Vis)nßB' = 0.048 L/s
(18) Minimum pumping power
Hp = Ps*qo = 0.176 KW
(19) Total P
Ht =
(20) Temper
ΔT =
Required accuracy achieved, iteration stops!
Finished
Optimization
Expert's analysis
Results output
Expert's analysis:
D: Please use the value given by the system.
a: Please use the value given by the system.
b: Please use the value given by the system.

(u)


Design
Multi-constraint optimization module (Output Card)
Please use following bearing parameters value given by the system
1. Basic parameters constrained by machine design:
Extreme load: W = 3500 N
Bearing diameter: 71.30 ≤ D(mm) ≤
Bearing length 71.30 ≤ L(mm) ≤ 71.47
Shaft rotation speed N ≤ 2000 rpm
2. Selected basic parameters:
Recess number. n= 6
Power ratio 1 ≤ K ≤ 3
Axial slot width c=
Axial-flow land width a= 17.8 mm
Radial clearance 0.05 ≤ ho(mm) ≤
Circumferential-flow land width b= 12.5 mm
Pressure ratio 0.4 ≤ ß ≤ 0.7
3. Parameters:
Minimum film thickness: hmin= 0.03 mm
Lubricant viscosity Vis
Supply pressure 3.66 ≤ Ps [MN/sq m] ≤ 3.67
4. Performance data:
Temperature rise. ΔT≤ 4.41 °C
Film stiffness
Flow rate. qo= 0.04 L/s
Pumping power: Hp≤ 0.18 KW
Total power. Ht≤ 0.53 KW
Optimization
Browse...
About...

(v)

Design

Design of capillary restrictors

Compared to other types of restrictor, capillary restrictors have several advantages which make them a popular choice

(1) manufacture is simple.

(2) capillary control gives the greatest tolerance to manufacturing variances in bearing clearance.

(3) with capillary control the bearing load and stiffness are independent of fluid viscosity and hence of temperature rise.

Four possible methods of making capillary restrictors are

a. hypodermic tubing (commercially available);

b. glass capillary (commercially available);

c. drilling;

d. spark machining.

Methods c and d do not usually produce pure capillary action since the length-to-diameter ratio obtainable is insufficient. Flow through a capillary should be laminar, it is therefore necessary to check that the Reynolds number is less than 2000.

(w)

Design

Design procedure of a capillary restrictor

Known parameters:

(1) Liquid density: ç = [780] Kg/cubic m

(2) Capillary diameter: dc = [0.0035] m

(3) Capillary ratio of length-to-diameter: l/dc = [200]

(4) Capillary length: l = [ ] m

Design

System I/O Board

The fluid flow is in the laminar flow condition

Design computation procedure:

(1) Liquid density

[ç] = [780] Kg/cubic m

(2) From known Kc and l/dc, capillary diameter dc can be determined

[dc] = [0.0035] m

(3) Capillary length [l] = [0.7] m

(4) Reynolds number [Re] = 4çqo/(π.dc.Vis) = [721]

(x)

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